# How Cost-Effective Is Forestry for Climate Change Mitigation?

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**Abstract** Cost-effectiveness analysis is important in focusing policies on minimising the costs of meeting climate change mitigation targets and other policy goals. This chapter provides a review of previous cost-effectiveness estimates of forestry options and underlying approaches, focusing especially upon UK studies, and setting the estimates in the context of those for other mitigation measures. Methodological issues such as discounting affecting estimates are discussed and existing evidence gaps highlighted.

For the UK, research gaps include evidence on impacts of afforestation on forest soil carbon balance, on comprehensive GHG balances for forest stands, on carbon stock changes during early tree growth and once stands reach maturity, and carbon substitution (or displacement) benefits. Better evidence is also needed on opportunity costs and on leakage effects.

Existing evidence indicates that forestry options are generally cost-effective compared with a range of alternatives. Whether this conclusion holds in particular cases will vary between projects and regions, as well as being dependent upon the approach adopted. To the extent that cost-effectiveness estimates depend upon the methodology adopted and benchmark used, future comparisons could benefit from greater methodological transparency and consistency.

Not only may forestry options be relatively cost-effective but, given the challenging task of reaching current targets, they are likely to be critical if existing international objectives on climate change mitigation are to be met.

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# 1 Background

Cost-effectiveness analysis is important in focusing policies on minimising the costs of meeting climate change mitigation targets and other policy goals. However, underpinning assumptions and approaches to estimating the cost-effectiveness of forestry measures vary. This chapter provides a review of previous cost-effectiveness estimates of forestry options and underlying approaches.

Before focusing on cost-effectiveness issues, the remainder of Sect. 1 provides a summary of background information on global carbon balances and climate change, and on the global and UK potential for forests to contribute to climate change mitigation. Section 2 discusses a range of methodological issues that affect cost-effectiveness estimates. Section 3 discusses the range of cost-effectiveness estimates made to date, focusing primarily upon those for UK forestry, and sets these estimates in the context of carbon prices derived in other ways. The final section offers some tentative conclusions and highlights existing research gaps.

## *1.1 Global Carbon Balances and Climate Change*

Evidence from ice core data indicates that the current concentration of atmospheric carbon dioxide ($CO_2$) is unprecedented in the past 800,000 years (Lüthi et al. 2008), with data from boron-isotope ratios in ancient planktonic shells suggesting that it is likely to be at its highest level for about 23 million years (Pearson and Palmer 2000; IPCC 2001, Fig. 3.2e, p. 201). Anthropogenic carbon emissions rose by 70 % between 1970 and 2004, from 29 to 49 thousand million tonnes of carbon dioxide equivalent ($GtCO_2e$) per year (IPCC 2007a), with global emissions rising by 3 % a year since 2000 (Peters et al. 2013). The current atmospheric concentration of $CO_2$ of over 390 parts per million (ppm) (Arvizu et al. 2011), which is around two-fifths higher than the pre-industrial level of about 280 ppm, is currently rising at an annual rate around 2 ppm (IPCC 2007a; GCP 2012; $CO_2$Now 2013).

As atmospheric $CO_2$ concentrations have increased over the past 150 years, the mean global temperature has risen. In the absence of new policy action, annual world greenhouse gas (GHG) emissions could rise by a further 70 % by 2050, and lead to a rise of 4 °C, or possibly 6 °C, above the pre-industrial global mean temperatures by the end of the century (OECD 2009), with greater temperature rises likely in some regions, including the Arctic (IPCC 2007a, Fig. 3.2, p. 46). Likely adverse impacts associated with exceeding a 1.5 to 2.5 °C temperature increase include increased risk of extinction of around 20 % to 30 % of plant and animal species, with many millions more people expected to be at risk of floods due to sea level rise by the 2080s (IPCC 2007a). Warming could lead to positive feedbacks that magnify temperature changes. These could include potential dieback of Amazon rainforest if warming exceeds 3 °C (see Lenton et al. (2008) and discussion in Dresner et al. (2007)). Thawing of the permafrost and subsequent soil decomposition could lead to the further release of up to 380 $GtCO_2e$ under a high warming

(7.5 °C increase) scenario by the end of the century (Schuur et al. 2011). Recent evidence shows that warming of the Arctic is occurring faster than had been predicted, with sea level rising more rapidly than expected (Le Page 2012).

In order to prevent 'dangerous climate change', international agreements reached at Cancun (UNFCCC 2011, paragraph 4) and under the Copenhagen Accord (UNFCCC 2010, paragraphs 2 and 12) call for limiting the average global temperature rise to no more than 2 °C above pre-industrial levels, with consideration of adopting a limit of 1.5 °C. To be confident of limiting the mean global temperature rise to between 2 °C and 2.4 °C is thought to require stabilisation of atmospheric GHG concentrations in the 445 to 490 ppm range, with reductions in annual global carbon emissions occurring no later than 2015, and emissions 50 to 85 % below 2000 levels by 2050 (Arvizu et al. 2011). However, some scientists have argued that even the existing GHG atmospheric concentration, which, including the effect of other GHGs, is equivalent to around 430 ppm $CO_2e$ (Trumper et al. 2009), is too high for the temperature rise to stay below the 2 °C threshold. Ramanathan and Feng (2008), for example, argue that the increase in atmospheric GHGs since pre-industrial times to date probably commits the world to a warming of 2.4 °C (1.4 to 4.3 °C) above the pre-industrial level during the current century – although some underpinning assumptions have been argued to be over-pessimistic (e.g. Schellnhuber 2008). Hansen et al. (2008) also recommend a rapid reduction from the current concentration by around 10 % to no higher than 350 ppm of $CO_2$. The difficulties of achieving such a target are discussed in the final section.

## *1.2 Global Potential of Forestry for Climate Change Mitigation*

Historically, forests in pre-agricultural times are thought to have covered around 5,700 million hectares globally, and to have stored around 1,200 thousand million tonnes of carbon (GtC) in total, including 500 GtC in living biomass and 700 GtC in soil organic matter (Mahli et al. 2002). Forests currently cover about 4,000 million hectares and, excluding woodlands under 0.5 ha, or primarily within agricultural or urban land uses, are estimated to store around 650 GtC, including around 290 GtC both in forest biomass and in soils, and 70 GtC in deadwood and litter (FAO 2010, Table 2.21). While comparisons are sensitive to definitional issues such as the depth of soil carbon covered, the latter estimates imply that the amount currently stored is of a similar order of magnitude to the total amount of carbon now in the earth's atmosphere: this is currently around 800 GtC (Lorenz and Lal 2010; Riebeek 2011).

Forestry has a potentially very significant contribution to make globally and might contribute two-thirds of the total climate change mitigation potential of land management activities (Mahli et al. 2002). There are two principal ways in which it can contribute.

Firstly, deforestation is a major source of GHG emissions. This is the reason, for instance, that forestry was the third largest source of global emissions in 2004, accounting for around 17 % of the total in that year (IPCC 2007a, Fig. 2.1, p. 36). It

is also the reason that it has contributed an estimated 45 % of the total increase in atmospheric $CO_2$ since 1850 (Mahli et al. 2002). In the absence of mitigation efforts, deforestation could result in an increase of 30 ppm in atmospheric $CO_2$ by 2100, making stabilisation of atmospheric GHG concentrations at a level that avoids the worst effects of climate change highly unlikely (Eliasch Review 2008). Reducing emissions from deforestation and forest degradation (REDD) is therefore a very important climate change mitigation activity if the international community's current climate stabilisation aspirations are to be met, especially in countries where the level of annual deforestation is high.

Secondly, afforestation and reforestation activities can make significant contributions to sequestering atmospheric carbon, as well as providing a renewable source of energy and materials to substitute for use of fossil fuels and more fossil-carbon-intensive materials. By itself, carbon sequestration by forests is best viewed as a component of mitigation strategies – however, it is far from sufficient to sequester total emissions from burning fossil fuels. Under business-as-usual scenarios global emissions from burning fossil fuels may be of the order of 1,800 to 2,100 GtC over the twenty-first century, exceeding the maximum potential human-induced forest carbon sink by a factor of 5 to 10 (Mahli et al. 2002).

### *1.3 UK Potential of Forestry for Climate Change Mitigation*

In total, UK forests are estimated to store around 162 million tonnes of carbon (MtC) in tree biomass, with a further 46 MtC estimated to be stored in forest litter and the top organic (F) layer of forest soils. Including soil carbon to a depth of 1 m, UK forests are estimated to store a total of 878 MtC (Morison et al. 2012, Table 2.1).

Britain cannot become carbon-neutral through domestic woodland creation alone (Broadmeadow and Matthews 2003). Nonetheless, considerable scope exists for increasing forest cover from the current low base to raise the contribution of British forests to climate change mitigation.

The 2010 UK Greenhouse Gas Inventory (Brown et al. 2012, Tables ES2.1 and ES2.2, pp. 10–11) indicates total net UK emissions of 590 million tonnes of $CO_2$ equivalent ($MtCO_2e$) in 2010, including the effect of carbon sequestration due to afforestation since 1990 and management of existing forests, which *removed* an estimated 3.6 $MtCO_2e$. Including areas afforested during the period 1921–1990, the contribution of UK woodlands to climate change mitigation is much greater than the level counted towards meeting the UK target under the Kyoto Protocol. (Changes associated with planting forests up to 1990 are not accounted for under the Protocol as they are treated as part of the baseline.) Estimates from the same model used for the UK Greenhouse Gas Inventory show total net carbon sequestration by UK woodlands rising from 2.4 $MtCO_2$ in 1945 to a peak of 16.3 $MtCO_2$ in 2004, before falling to 12.9 $MtCO_2$ in 2009 (Valatin and Starling 2011). Uncertainty remains over the precise magnitude of the UK forest sink, however, with estimates of current net uptake (after taking account of removals of around 6.5 $MtCO_2$ due to harvesting) ranging between 9 and 15 $MtCO_2$ (Morison et al. 2012).

There are currently 3 million hectares of woodland in the UK, accounting for around 12 % of the UK's total land area, a proportion far below the average for the EU as a whole of 37 % (FAO 2010). The impact of expanding UK woodland cover by about a third to 16 % by increasing woodland creation to 23,000 ha per year (an extra 14,840 ha per year above the current level) was considered by Read et al. (2009). Based upon a scenario which involves creating a mix of high-yielding short rotation forestry, broadleaf and conventionally managed coniferous woodlands, and underpinning assumptions (e.g. yield classes), this was estimated to increase the net carbon sequestration by UK forests planted since 1990 to over 10 $MtCO_2e$ (Read et al. 2009). Including carbon substitution benefits, total abatement was estimated to rise to 15 $MtCO_2e$ by the mid 2050s. This is equivalent to about one tenth of the total UK GHG emissions at that time if current emissions reduction commitments are achieved (Read et al. 2009), although approaches to ensuring that associated carbon sequestration benefits are maintained in perpetuity were not discussed.

## 2 Techniques and Issues in Cost-Effectiveness Assessment

Cost-effectiveness is an economic efficiency measure, in general terms evaluating the cost *per unit of achievement* of the desired objective. It is often employed when a target level of achievement is *given*, and what is sought is the best way of achieving it. It may be contrasted with optimality measures, which seek to achieve the *most desirable* level of an objective, given some trade-off between achieving it and the cost of doing so. In the context of climate change, optimality may be considered to entail the best balance between on the one hand the benefits that accompany continuing generation of GHGs (i.e. normal economic activity), and on the other the costs of the consequent climate change. However, where climate change impacts are highly uncertain, optimality may be indeterminate. (See also discussion of intergenerational and other ethical issues in Sect. 2.8 below.) Cost-effectiveness analysis is most appropriate when a target (e.g. limiting global average temperature rise to no more than 2 °C above pre-industrial levels) has been agreed and where the issue addressed is how to ensure the target is met at least total cost.

The appropriate cost-effectiveness measure for $CO_2$ mitigation is in essence very simple. The extra cost (financial or social according to context) of deploying the $CO_2$ mitigation measure – compared with the cost of *not* deploying it, is divided by the extra reduction in the atmospheric carbon level achieved by deploying the measure – compared with the level of carbon reduction ensuing if the measure is *not* deployed. In general terms, this is expressed as:

$$\frac{[\text{Net cost of the measure}] - [\text{Net cost of 'do-nothing' measure}]}{[\text{Carbon reduction of the measure}] - [\text{Carbon reduction of 'do-nothing'}]}$$

For non-forestry options there may be a one-off cost to achieve a single pulse of mitigation. This may become more complicated if there is a cost of maintaining sequestration, as for example in geo-engineering or carbon capture and storage options where there is a requirement for on-going monitoring and maintenance of the system. Carbon-fixing agricultural practices may also produce a one-hit outcome contemporary with cost, as when a less fuel-intensive practice is used, or when an annual crop is harvested as bioenergy.

In assessing forestry, problems include the time profiles not only of costs, but also those of carbon fluxes. For afforestation options there is year-on-year sequestration whose rate may not reach a maximum for many decades, especially in temperate or boreal conditions. For commercial regimes, there is also a discrete series of removals from the crop. Similarly, for such options as adopting reduced-impact logging in place of conventional logging, there is an immediate differential in the carbon removed from the forest, then a long period over which carbon biomass is re-established, but not necessarily at the same rate or to the same carbon stock with the two logging systems (Healey et al. 2000). To resolve these profile problems it is necessary to adopt some means of integrating fluxes over time, or defining a mean level of added sequestration. The two main approaches focus on respectively the fluxes and the stock of carbon sequestered. The flux approach may best be envisaged in terms of a price for the service of actively locking up carbon. It may be given by calculating the price for a unit of carbon's being locked up (i.e. for a carbon reduction) which would just suffice for the option to break even, including also as a debit any subsequent revolatilisation of the carbon by burning or decay. In cases where the discount rate is assumed constant, the derivation of that price is as follows; the issue of discounting cash flows and carbon fluxes is treated later.

For investment in forest carbon fixing to break even,

$$\left[\{\text{difference of}\}\text{summed discounted cost}\right] =$$
$$\left[\{\text{difference of}\}\text{summed discounted carbon credits}\right] =$$
$$\sum_{t=0}^{t=T}[\text{carbon price}]\times[\{\text{difference of}\}\text{flux}]_t \div (1+[\text{discount rate}])^t =$$
$$[\text{carbon price}]\times\sum_{t=0}^{t=T}[\{\text{difference of}\}\ \text{flux}]_t \div (1+[\text{discount rate}])^t$$
$$\text{whence } [\text{carbon price}] =$$
$$\frac{[\{\text{difference of}\}\ \text{summed discounted cost}]}{\{\text{difference of}\}\ \sum_{t=0}^{t=T}[\text{flux}]_t \div (1+[\text{discount rate}])^t}$$

Where the discount rate changes through time, as under current UK Treasury advice, the term '$\div(1+[\text{discount rate}])^t$' is replaced by a discount factor compounded from the relevant discount rates for the relevant periods: e.g. for 50 years the discount factor is '$\div\{(1+3.5\ \%)^{30}\times(1+3\ \%)^{20}\}$'.

Such a price may properly be compared with mitigation costs calculated for non-forestry options if the carbon price is assumed constant over time. Where carbon prices are anticipated to change over time, comparisons based upon the above approach have either:

- To be confined to options that have the same profile of fluxes over the same time horizon; or
- To include some means of weighting fluxes according to relative price, most readily achieved by using a price-adjusted carbon discount rate.

By contrast, the stock approach considers the forest to be 'renting out' the service of maintaining carbon in a sequestered state for one time period, normally a year. The break-even cost of doing so is the annual cost of retaining an equilibrium condition in the forest stock. This equilibrium may represent a fully-developed [semi-]natural forest in which the composition of tree sizes remains the same from year to year; or the mean over a rotation period of the carbon stock in a growing forest; or, what is equivalent, the mean carbon stock averaged over all the age-classes in a normal forest.

To compare this rental value with the mitigation costs of non-forestry options it is necessary to render the latter as an annual cost of *maintaining* each tonne in a sequestered state. Or, where a constant discount rate is applied, the total discounted costs of *achieving* permanent sequestration of a tonne may be converted to an annuity, by multiplying them by whatever discount rate is deemed appropriate. Such an approach would be especially suitable in the context of steady-state economies – a popular concept in some circles.

Since they refer to different durations of carbon lock-up, the flux and stock approaches will not normally give similar prices per tonne. Where the time profiles of cost and of sequestration differ between options, they may not even give the same ranking of cost-effectiveness within a given set of options. More fundamentally, divergence can also arise where carbon storage in existing woodlands is treated as a benefit under the stock approach, but not under the flux one. Existing carbon storage is treated equally as a benefit under both approaches in the case of REDD projects.

## *2.1 Issues: Units*

Much confusion has been caused in the past by failure to specify or recognise the unit of achievement. Measures commonly used include 'cost per tonne of carbon', 'cost per tonne of $CO_2$' (removed from or emitted to the atmosphere), and 'cost per tonne of $CO_2$ equivalent' (the last measure being used in making comparison with other greenhouse gases or with other mitigation measures). For example Ayers and Walter (1991) seem to have been early users of the $\$/tCO_2e$ measure, without making this clear, and found themselves in phantom conflict with other authors, who were using \$/tC. According to context, one or other of these may be considered the most appropriate, but it is of the first importance to ensure that figures drawn together

from different sources all have the same basis, or are converted to so being. For example, because carbon constitutes about 12/44 of the mass of $CO_2$, cost given as 'per tonne $CO_2$' can be converted to 'per tonne carbon' by multiplying by 44/12. Since carbon is incorporated in different molecular structures during its transactions between earth, vegetation, atmosphere and ocean, there is something to be said for the 'per tonne carbon' measure.

Where there are other significant GHG fluxes, these can be converted to a 'per tonne of carbon dioxide equivalent' ($tCO_2e$) based upon their global warming potential compared to the 'radiative forcing' (measurable in terms of the increase in equilibrium temperature caused) of emitting a tonne of carbon dioxide. This entails complex modelling of, among other things, 'natural' uptake of atmospheric $CO_2$ into oceans and terrestrial ecosystems, particularly boreal forests, as well as parallel modelling for the options considered as alternatives. Global warming potential is defined as an index, usually computed as the cumulative radiative forcing over an arbitrary 100 years, compared to emitting a unit of carbon dioxide. Over this time-frame, the other GHGs have higher (up to 23,900 times higher – in the case of sulphur hexafluoride) global warming potentials than carbon dioxide, molecule for molecule (Brown et al. 2012, p. 39). The current preference of the UK government for using $tCO_2e$ (e.g. HM Treasury and DECC 2012) arguably reflects best the primary concern with the impact of changes in atmospheric GHG balances and with using a metric that facilitates comparisons between sectors.

For climate impacts other than through reducing GHG concentrations, the appropriate cost-effectiveness measure would also be cost per unit of reduced radiative forcing. Forestry examples include impacts of afforestation on solar radiation reflectivity (the 'albedo effect') and of increased release of water vapour from forests ('evapotranspiration') on cloud cover and associated reflection of solar radiation, as well as in reducing surface temperatures. Jarvis et al. (2009) suggest that UK afforestion in general has little effect on albedo because forests' solar reflectivity is similar to that of previous vegetation, but precise calculations have not so far been done for UK conditions. Over a typical rotation increased solar radiation absorption by conifers compared with grassland may reduce the climate change mitigation benefits from carbon sequestration and substitution by 20 to 35 %, depending on conditions (James Morison, personal communication). Jarvis et al. also argue that any impact on cloud cover is likely to be small as existing UK weather patterns are generally determined at much larger scales, over the Atlantic Ocean, Europe and Russia.

## *2.2 Elements in Forest Sequestration*

Carbon is locked up in the chemical components of trees, litter, soil, and wood products (especially those that are durable). Physical and economic valuations have differed in their focus on these, some concentrating on the trees themselves (Price and Willis 1993); others on soil (Cannell et al. 1993); others on wood products (Price and Willis 2011); while yet others have tried to incorporate all elements (Brainard et al. 2009).

The rate of accumulation of carbon in trees has long been a subject of physical study, modelling and economic analysis (Price 1990; Dewar and Cannell 1992; Olschewski and Benitez 2010). With appropriate conversion factors, tabular or parameterised yield models can give the required data: development of models that incorporate expected impacts of climatic changes on yields being a current research frontier.

Leaf and branch litter is a significant store of sequestered carbon, and a forest soil may contain more carbon per unit ground area than even the mature forest trees. It is an important matter, therefore, whether and how the silviculture affects the soil carbon stock (Jandl et al. 2007). This remains an ongoing area of research. In the UK, for example, there is currently considered to be insufficient data to quantify with confidence changes in soil carbon associated with afforestation (Morison et al. 2012).

After harvesting, sequestered carbon may remain in forest products for periods as short as a few months (paper) or as long as millennia (structural timbers). For example, millions of $tCO_2e$ may be locked up in the roofs and fitments of Britain's medieval churches.

Forest operations consume fossil fuel and emit carbon, with most emissions within the forest occurring during harvesting, and subsequent haulage to the primary processor representing the largest source of emissions overall. However, fossil fuel usage during forestry operations (road building, ground preparation, thinning, harvesting and timber haulage) is relatively minor compared with the level of net carbon uptake by forests. In the UK these forestry operations have recently been estimated (Morison et al 2012) to result in total annual emissions of 0.22 $MtCO_2$ (a level around 1 to 2 % of net carbon uptake). This includes total emissions from harvesting of 0.07 $MtCO_2$ (a level under 1 % of net uptake).

Since all these represent components in the overall forestry carbon and GHG balance, it should be beyond question that, where significant, all are included in evaluation of forestry's cost-effectiveness for mitigation. However, some stores such as in the biomass of trees are readily measured and predicted, while other factors such as soil processes or the product life span are less predictable. These are not just issues for scientists, but are reflected profoundly in the economic evaluation.

### *2.3 Additionality and Leakage*

Because in the real world comparison must always be made with what would happen in the absence of the specified measure, there is a potential problem in specifying the counter-factual: in economics, it could be said, the most important question is 'what changes? what difference does it make if I do this, rather than not-doing this?' This raises questions of 'additionality' (what changes within the specified project boundary) and 'leakage' (what changes outside the project boundary).

Although approaches to additionality vary and its determination is imprecise to the extent that it is based upon comparisons of future hypothetical scenarios

(Valatin 2011a), the key issue is: what change in the GHG balance, over and above what would otherwise have existed, is the consequence of a particular mitigation activity? Richards and Stokes (2004) identified additionality and leakage as particularly important problems for forestry sequestration studies.

Within forestry, the 'do-nothing' option may not be carbon neutral. Land abandoned for agriculture may, in time, accommodate a natural succession of vegetation whose end-point is a mature forest, perhaps one capable of storing more carbon than a human-made forest on a commercial rotation. Asked what would happen in the absence of their enrichment planting in a cut-over tropical forest, one agency that was drawing down funds for enhanced carbon storage said that the forest would probably regrow naturally anyway. What, then, would change as a result of enrichment planting? In terms of the final carbon storage, possibly nothing, although speeding the carbon accumulation could accelerate mitigation benefits. Contrariwise, not maintaining tree cover on steep slopes may lead to erosion and loss of soil carbon.

Less obvious is the effect of adding wood products to a world market, compared with *not* supplying them. If the UK increases its output of construction-grade timber, is the consequence that more timber is used in buildings? If so, is that through buildings' being larger (and thus needing more heating), or through displacing other, fossil-carbon-intensive materials? Or would UK timber displace imports from Scandinavia, Russia or North America? In this case, would reduction in timber exports from those regions lead to a greater accumulation of carbon in less-managed forests, or a carbon-reducing conversion to agriculture as forestry became a less economically viable activity? Such effects on 'invisible stakeholders' have not customarily entered economic analysis (Price 1988, 2007), and they are seldom mentioned in publications, but they could affect significantly both financial and carbon accounts of forestry.

Evidence from US studies is reported to imply that 'leakage', can range from 5 % to 93 % of project abatement benefits depending upon the activity and region (Murray et al. 2004; van Kooten et al. 2012). A primary concern is that conservation of domestic forests will lead to increased timber harvesting and environmental degradation in other countries (i.e. indirect land use change), with a lesser concern being that it may result in use of more energy-intensive materials (Gorte 2009). However, research on quantification of international leakage effects appears sparse, with a recent review (Henders and Ostwald 2012) relating to REDD projects identifying just two items. Both involved modelling exercises based upon complex data inputs, and are not currently used in practice for forestry projects under the voluntary carbon market standards considered.

More recognised is that afforestation involves withdrawal of land from agriculture, which has its own effects on soil carbon (Moran et al. 2008); on operational fossil fuel use; and on the carbon transactions of affected food imports (Hockley and Edwards-Jones 2009). If lost food production is replaced by intensification of agriculture on other land, the ensuing fossil fuel use and consequent $CO_2$ emissions would need to be considered too.

*Other* mitigation measures also present an adjustment from a do-nothing position that itself has consequences for carbon storage, via the adjustments of production and consumption technologies that accompany changing market conditions.

At present it is believed that no adequate examination of these complex secondary effects has been concluded. Richards and Andersson (2001), for example, noted that estimating the off-site effects of individual carbon projects is an onerous task as it requires analysing shifts in supply functions for forest products, agricultural products and agricultural land. In many countries suitable general equilibrium models (or even the requisite time-series datasets to build such models) may not currently exist, or be considered too costly to develop.

Leakage due to the potential for afforestation to result in deforestation of other areas is not an issue within the UK owing to the existing regulatory requirements for an environmental impact assessment for deforestation over 1 ha (0.5 ha in sensitive areas), for re-stocking of areas felled, and for protection of biodiversity and semi-natural habitats. The approach to leakage adopted under the Woodland Carbon Code (Forestry Commission 2011b) developed for UK forest carbon projects includes not accounting for reductions in GHG emissions associated with the cessation of the previous (e.g. agricultural) land use. This allows for the potential intensification of activities (e.g. agriculture) elsewhere in the UK. However, GHG emissions associated with any resultant more intensive use of land under the same ownership or lesseeship have to be accounted for in calculating the net carbon sequestration of a project (Forestry Commission 2012). As it currently just covers afforestation, leakage associated with forest conservation projects (the main focus of US studies) is not an issue at present for UK projects under the Code.

## *2.4 Treatment of Volatilisation and Repeat Projects*

At the end of a commercial forest rotation, and often at intermediate times, timber is removed. The issue here is how this removal is treated within carbon accounts.

- It could be debited from the forest account, and credited to the account of the recipient.
- It could be taken as instant loss to the global fixed carbon account.
- Progressive return of the carbon to the atmosphere as $CO_2$ could be profiled as a generalised volatilisation, according to some specific functional form (Brainard et al. 2009).
- The volatilisation process could be disaggregated so as to occur at various rates according to product category (Thompson and Matthews 1989).
- The forest could be taken to sequester the long-term average level of carbon under the existing management regime (e.g. perpetual series of commercial rotations, or biological maturity if no harvesting is envisaged), so that this level of carbon stays permanently sequestered. (The fiction is sometimes perpetrated that, once the forest has grown to commercial rotation, that level of carbon remains permanently sequestered, while successor rotations add perpetually to the sequestration – despite the fact that this clearly cannot be the case).

Although which treatment is most appropriate may depend upon the purpose of the analysis, the UK Woodland Carbon Code (Forestry Commission 2011a) assumes that the long-term average carbon stock is maintained. In effect, once the long-run average level is attained, this results in placing an equal value on the capture and release of carbon. However, as capture tends to precede release, where a positive discount rate is used (and the carbon value is not increasing over time), the 'discounted tonnes' of capture will exceed those of release. Although the overall effect may be small, to the extent that this positive balance of 'discounted tonnes' is considered an abatement benefit, not taking it into account may tend to result in the net cost of projects being over-estimated.

Volatilisation is not so much an issue for assessments in which forests' sequestration is rented for fixed periods, as is the case under temporary storage certificates (Olschewski and Benitez 2010).

Volatilisation also becomes much less of an issue with a high discount rate, because of its occurrence late in the cycle (the same reason that tends to make forestry unprofitable with high discount rates).

With sufficient lapse of time (many centuries), nearly all the carbon sequestered by a single cycle of commercial forestry returns to the atmosphere, because ultimately all wood products (including biomass) decay or are otherwise oxidised (Price and Willis 1993). A perpetual sequence of rotations, which is the ground of sustainable forest management and the base assumption of classical forest economics, repeats the fluxes of the first, endlessly. But clearly its sequestration is not cumulative, apart from any accumulation of carbon in soil and litter layers, or unless some means is found of permanently preserving the harvested timber, or except in relation to recurrent displacement of fossil-carbon-intensive materials.

### *2.5 Combustion and Structural Displacement*

In addition to storing carbon directly, forest products may be beneficial in displacing fossil-carbon-intensive materials such as steel or concrete. Use as biofuel also displaces combustion of fossil fuels, but necessarily involves instant and complete revolatilisation of sequestered carbon.

Inclusion of such functions may dramatically increase the profitability of forestry (Price and Willis 2011). Obversely, they may substantially reduce cost/t$CO_2$e, in forestry options that involve such commercial removals.

This is an area where, for the UK at least, significant scope remains for improving existing estimates of the associated abatement benefits (Morison et al. 2012).

### *2.6 Net Costs*

To speak of 'the climate change mitigation cost' of forestry options is to assume that forestry is an unprofitable investment, or that it would not in any case be undertaken for a range of purposes. Offsetting its costs are revenues from sale of products and, in a public context, the value of providing net non-market benefits. These should be,

and in some cases have been, deducted from costs in deriving a supply price for carbon sequestration services. In some circumstances a negative net cost will arise.

Mitigation cost is a concept of practical significance only in relation to additional forestry options, ones that would not be undertaken in the absence of carbon benefits. However, even where costs are negative (i.e. a project would have been expected to go ahead in the absence of carbon benefits), the mitigation cost may be of policy interest in comparing costs of different measures and developing marginal abatement cost curves.

Cost estimates may be based upon the costs to the private sector of implementing measures, or the social costs to the economy as a whole. The latter may extend to considering transaction and policy implementation costs, and ancillary costs and benefits, including life-cycle analysis of effects in related sectors.

## *2.7 Opportunity Costs*

Agricultural opportunity costs may constitute the largest element of the cost of woodland creation measures. However, these vary widely. In some cases (e.g. where the most marginal land is used) the opportunity costs of converting farmland to woodland may be minimal, or even negative where environmental impacts associated with existing agricultural practices (Spencer et al. 2008) are accounted for, or where farming's profitability is only achieved through subsidy. (For example, a recent survey of UK agriculture (Defra et al. 2010, Table 2.5, p. 9) reports that almost a quarter of farms (22.1 %) had a net farm income below zero). This is an area where, for the UK at least, work to improve upon previous estimates is needed, including how statutory requirements for woodland cover to be subsequently retained in perpetuity affect the value of land converted from agricultural or other uses (Valatin 2012).

## *2.8 Discounting and Time Horizon*

As will rapidly become apparent, the effect of discounting is not only of great importance in relation to climate change: it is also one of the most contested areas in natural resource economics. The authors are not necessarily in agreement over all the issues, and where this is so we have tried to make that plain.

### The Case for Discounting

The general position of economists, and that of the UK Government, is that cash flows (of costs and benefits measured in current prices) should be discounted. The main justifications have been as follows:

- Financial resources can be invested to yield net revenues. Thus they have an opportunity cost in reduction of what other benefits can be generated in future, if cash flows are expended early or are received late. Alternatively, the later that

costs occur, the smaller the sum that needs to be invested presently in order to provide compensation for future costs, since the period of growth of the compensation funds will be longer.

- People have an innate *time preference*, for early rather than late consumption, and a democratic government should respect that wish.
- Assumed future growth of income and consumption per capita entails diminishing marginal utility – a reduced significance of additional units of future consumption, or a lower opportunity cost of resources diverted from consumption in order to deal with environmental and social problems.
- The possibility exists that devastating events will eliminate, or radically and unpredictably alter, future returns (HM Treasury 2003), or result in human extinction (Lowe 2008).

In addition, concerns about the potential for exceeding critical tipping points combined with uncertainty about precise thresholds could be viewed as providing a reason for prioritising early abatement, either by valuing it more highly than later abatement (because of the longer period of ensuing benefit), or by discounting later abatement (Valatin 2011b).

### The Case for Not Discounting Carbon Fluxes

Not discounting carbon fluxes generally implies that a tonne of carbon sequestered at the end of a 100-year rotation is as important as one sequestered immediately. Such an approach would be consistent with an intergenerational justice argument, that the costs of climate change to future generations, howsoever or whensoever caused or mitigated, ought to be treated at parity with costs to the present generation.

However, if issues of intergenerational equity forbid the discounting of carbon fluxes, why should they not also forbid discounting wood fluxes, or for that matter cash flows? If discounting *is* justified for benefits and costs generally, morally relevant differences should be shown why it should *not* be applied to carbon.

From a rights-based perspective, Spash (1994) notes that harms inflicted on future generations due to continuing GHG emissions are in no way balanced out by benefits enjoyed by the current generation in their use of fossil fuels (see also Spash (2002)). To the extent that preventing the most significant avoidable future harms is considered a moral imperative, this could be viewed as providing an ethical basis for not discounting either the causes *or* the effects of climate change.

Similarly, drawing upon Principle 1 of the UN Conference on the Human Environment 1972 Stockholm Declaration and a 2008 UN Human Rights Council resolution, Caney (2010) argues that persons have a human right to a healthy environment and that climate change poses a far-reaching threat to the enjoyment of this right by current and future generations. But note that similar arguments could apply to other actions which cause significant avoidable harm to future generations. It might be argued that in some circumstances ‘avoidable harm’ could include failing to provide wood and other natural resources that might be vital to future well-being.

Furthermore, inconsistencies could arise if equity/rights-based perspectives (not discounting the causes or effects of climate change), are combined with a preference for early abatement so that critical thresholds are not exceeded. This would imply the adoption of a different approach to GHG emissions (not discounting) from that for abatement (discounting), with increasing weight placed on emissions relative to abatement over time.

## Discounting and Not-Discounting Under the UK Government Approach

In former times the governmental view was that 'environmental costs and benefits should be discounted just like any other costs and benefits' (Department of the Environment 1991). The Stern Report, commissioned by the UK Government and pilloried by some economists for the *low* discount rate used, did in fact discount the value of *effects* of climate change on human welfare.

However, the present UK government approach to cost-effectiveness (HM Treasury and DECC 2012) is that carbon fluxes themselves (the *cause* of climate change) are not discounted. Whether the *value* of carbon fluxes should or should not be discounted depends, according to this approach, upon the focus of the analysis. Two broad 'sector' categories are distinguished.

Emissions associated with industrial sources subject to emissions reduction targets under the EU emissions trading scheme are categorised as occurring in the 'traded' sector. These include carbon emissions from energy (combustion installations over 20 MWth, mineral oil refineries, coke ovens), ferrous metals production and processing, building materials production (cement, glass and ceramics), pulp, paper and board manufacture, and (from 2012) civil aviation. (Inclusion of flights to and from countries outside the scheme has been delayed, however, while coverage of the scheme is to be extended to petrochemicals, ammonia and aluminium industries in 2013.) Sources in this 'traded sector' are currently responsible for almost half of total EU $CO_2$ emissions and around 40 % of total EU GHG emissions (European Commission 2012).

Emissions and abatement from sources which are not covered by the EU ETS are categorised as occurring in the 'non-traded' sector. These include sequestration in forests and many of the carbon displacement benefits associated with use of wood products.

As separate targets (and markets with different prices) exist for the two, carbon in each is *treated* essentially as a separate commodity, although of course the physical transactions take place with a common atmospheric pool of carbon. Carbon prices in the two sectors are currently projected to converge and equalise in 2030 as a functioning global carbon market is established (HM Treasury and DECC 2012, p.13).

### Discounting Abatement Benefits in Traded and Non-Traded Sectors

Although neither sectoral perspective involves discounting carbon fluxes per se, each does include the present value of any consequent fluxes in the other sector (which is computed by applying discounting).

Analyses from a forestry perspective, as part of the 'non-traded' sector, include the (discounted) present value of consequent fluxes in the 'traded' sector, such as those arising by substitution for fossil fuels in large-scale electricity generation. Contrariwise, analyses from the 'traded' sector's perspective include the present value of any forest fluxes – for example those of forests planted to yield those products.

Apart from the different treatment of carbon benefits, all project cash flows *are* discounted. Thus these would be the same, whichever sectoral perspective was taken.

Although their discounted value is taken into consideration, fluxes themselves in the other sector are not accounted for as part of the aggregate abatement associated with a project, and may thereby lose some of their significance.

### Implications of the Discounting Protocol

To the extent that the time profiles of fluxes in the two sectors differ, discounting in computing the present value of fluxes in the other sector will have a quantitatively different effect. Consequently, if it were the case that the level of abatement in both sectors was the same, the calculated cost-effectiveness of carbon mitigation in the overall project would be likely to appear different, depending on which sector perspective the analysis adopts.

In general the two sectoral perspectives are not viewed as alternatives, however: the perspective that should be adopted is that of the sector in which most of the mitigation benefits arise. A non-traded sector perspective is appropriate for most UK forestry projects as most of the carbon benefits occur in this sector.

Given that separate targets exist for the 'traded' and 'non-traded' sectors, from an institutional perspective it may seem logical that the present value of fluxes in the 'other' sector should be included in this way in analysis performed within one sector. From a global perspective, and given that $CO_2$ fluxes interact with the same atmosphere irrespective of the institutional source or sink, it may seem strange that different approaches to valuation of carbon fluxes within the two sectors are used and different social values of carbon applied. However, as social values applied in valuing carbon in the regulated (i.e. traded) sector are related to market prices applying within the EU ETS, it does not appear entirely surprising that those applying outside this compliance market have a different basis, even if the current ratio of the values in the two sectors (around 1:10 for the central estimates in 2013–2014) is remarkable.

It could be argued that not discounting the *causes* of climate change (carbon emissions) or the causes of mitigation (carbon sequestration) shows inconsistency in application of discounting. On the other hand, this may appear unimportant to the extent that the primary purpose of the protocol is to determine whether measures are cost-effective, and to allow comparisons of the cost-effectiveness of different options, rather than focusing upon levels of abatement per se.

### Declining Discount Rates

To the extent that equity/rights-based perspectives are consistent with discounting at all, they are arguably more consistent with using declining discount rates than with using the initial discount rate in perpetuity. Use of declining discount rates is currently the approach recommended for UK policy appraisal in the Treasury Green Book (HM Treasury 2003), based upon uncertainty about future values of time preference (Lowe 2008). For a discussion of the use of declining discount rates for policy, see OXERA (2002), Hepburn and Koundouri (2007), and Gerlagh and Liski (2012). For critiques of the approach, see Price (2005, 2010, 2011).

Again, however, it could be argued that if moral imperatives favour future reduction in discount rate, they would even more favour not discounting at all.

### Adapting Conventional Discounting: An Alternative Approach

A more conventional economic perspective is that the argument of diminishing marginal utility applies in principle – though not to an equal extent – to all things that may be enjoyed, suffered, compensated for or mitigated by the deployment of investment funds or material resources. This includes what is required to defend against the consequences of climate change. It is important to note, however, even within this perspective, that not all environmental values experience diminishing marginal utility – at all or at the same rate. The proper approach is not to discount carbon *fluxes* differentially, but to discount the *effects* of those fluxes differentially, according to the expected and various influence of diminishing marginal utility. For example, some biodiversity values may not be susceptible to diminishing marginal utility, whereas products based on technological advance may have very rapidly diminishing marginal utility (Price 1993, Chaps. 16–18). Under some scenarios marginal utility may diminish: under others (e.g. catastrophic disruption of the world economy) it may increase, the appropriate approach then being to take a mean of outcomes, weighted by their probabilities (Price 1997).

The human extinction/catastrophe argument may be considered a valid reason for discounting future effects, and has long been discussed in the literature (Price 1973; Dasgupta and Heal 1979). However, the inclusion of this rationale for discounting risks the promotion of a self-fulfilling prophecy. Discounting for the uncertainty that surrounds climate change reduces the weight given to the future costs of climate change, and so, perversely, increases the value ascribed to the most risky strategy, business-as-usual.

As for the time preference argument, it has long been regarded by economic philosophers as arising ‘merely from weakness of the imagination’ (Ramsey 1928), and indeed as representing a misinterpretation of what it is that people prefer (Price 1993, Chap. 7). It has no relevance to the value of the future *to* future generations, whether that is from the causes or the effects of carbon fluxes, or from any other environmental values, or from wood, or from any other material values.

Thus diminishing marginal utility remains as the ‘respectable case for discounting’: the return on investment funds is dealt with in other, more appropriate, ways of giving an opportunity cost (Price 2003).

### The UK Government Approach in Practice

Although on initial inspection the present UK government approach (HM Treasury and DECC 2012) might be interpreted to mean that a tonne of carbon sequestered is equally important irrespective of when it occurs, such an interpretation would be misleading for two reasons.

Firstly, some discounting may take place within forestry analyses (generally, in calculating the present value of any fluxes in the traded sector, as discussed in section “Discounting Abatement Benefits in Traded and Non-Traded Sectors”).

Secondly, although the cost-effectiveness estimate is derived without discounting forestry carbon fluxes themselves, discounting is applied to the value with which this estimate is compared, as follows. To determine whether forestry is an attractive option, the cost-effectiveness estimate is compared with the social value of a 1-$tCO_2e$ reduction in emissions (abatement) in terms of its contribution to meeting UK climate change mitigation targets. This comparator is taken as a weighted mean of the calculated social values of carbon at each of the times when abatement occurs, each of these being discounted according to the Treasury Green Book protocol, and is computed as:

$$\sum_{t=0}^{t=T} [\{\text{abatement}_t \div \text{lifetime abatement}\} \times \{\text{social value of carbon}_t \times \text{discount factor}_t\}]$$

Thus the timing of the abatement, while not affecting the cost-effectiveness estimate itself, does affect the value with which it is compared.

In judging whether a measure is cost-effective, the HM Treasury and DECC (2012) approach gives similar results to discounting the GHG savings in the sector and then comparing the estimate with a cost comparator computed as an undiscounted (abatement-weighted) social value of carbon (i.e. using the above formula but omitting the ‘× discount factor$_t$’ term). Despite similarities, hypothetical examples can be constructed to show that the two methods do not invariably give the same result (for further discussion see Valatin 2012, p. 4).

Whether lack of discounting the carbon fluxes (combined with the employment of discounting in computing the cost-comparator used to judge cost-effectiveness) permits an appropriate comparison of abatement levels remains a matter of debate between the authors. For one, it provides a transparent comparison uncomplicated by discounting or other subsequent potential transformations of fluxes, that could usefully supplement alternative perspectives. For the other, it obscures the following fact: to the extent – and *only* to the extent – that delay in the *effects* of climate change justifies discounting, then delay in the *causes* of climate change (GHG fluxes), equally results in less importance for those causes. A consistent appraisal should explicitly reflect this by discounting of fluxes, as deemed appropriate.

The authors are agreed that numerically the two approaches will yield similar results, given consistent assumptions about discounting. The implication is that the comparator does, *in its effect*, simulate the discounting of carbon fluxes (later fluxes have less influence on the comparator), whatever might be said about ethical considerations.

## Price Change and Discount Rate Adjustment

From the early days of climate change economics, it has been argued (Nordhaus 1991; Adger and Fankhauser 1993) that the economic impact of climate change will grow in line with gross world product (GWP): for example, because with advancing agricultural technology greater food production would be lost when a given area of farm land is inundated by sea-level rise; and because people will have larger houses to which air conditioning needs to be applied. If this is so, it is, arguably, correct to adjust the carbon price directly, rather than to subsume it in adjustment of the discount rate. This makes it possible to incorporate a number of factors that might be considered to affect the carbon price.

However, in the absence of such explicit adjustment, it is better to adjust the discount rate for carbon downwards by the margin of the best-guessed rate of carbon price increase, than to assume that the carbon price will remain constant. The practical advantage of adjusting the discount rate rather than increasing the carbon price over time – as done under the present UK government approach (HM Treasury and DECC 2012) – is that it simplifies calculations, and makes it easier to achieve consistency through the phases of evaluation (see Price in review).

Increasing carbon prices – and, equally, reduced carbon discount rates – can provide an incentive to delay abatement (Sohngen and Sedjo 2006; Murray et al. 2009). In fact a combination of low or zero discounting with a price rise for carbon makes it possible to generate a negative carbon account for a single-cycle forest sequestration and revolatilisation option (Price 2012). However, experience suggests that such cases do not arise for afforestation projects *where current UK government guidelines* (HM Treasury and DECC 2012) *are followed*. This is probably because discounted social values of carbon decline continuously after about the first 40 years, while future values for the 'non-traded' sector are generally below the initial value (see Valatin 2011b, Table IV and discussion of the evolution of the UK approach to determining the social value of carbon).

## In Summary

The discount rate debate has been extremely long-running (back to the time of Moses) and wide-ranging (embracing everything from trivial pleasures to human life itself). The reader is referred to numerous reviews for further argumentation (e.g. Lind 1982; Broome 1992; Price 1993, 2006; Portney and Weyant 1999).

As a consequence of the variation in abatement and cost profiles over time, cost-effectiveness estimates are sensitive to the time horizon and base year focused upon. In this sense, abatement cost estimates provide only a snapshot of cost-effectiveness at a specific point in time over a particular time-horizon.

### *2.9 Sensitivity to Assumptions*

The following table illustrates how the assumptions made concerning the above issues could significantly affect the cost derived. It is based on a spreadsheet model of forest stand growth and utilisation which includes both carbon fluxes and cash flows. Net cost is calculated according to normal net discounted cash flow procedures over a perpetual series of rotations. Carbon fluxes are included or not, and discounted or not, according to various protocols discussed above.

### *2.10 Risk*

Forestry's long production cycle, as well as the indefinitely prolonged residence of some $CO_2$ fluxes into or from the atmosphere, make calculations concerning climate change mitigation susceptible to great problems of prediction. Fire, storms, attack by pests and pathogens, human incursion and revisions of governmental or landowner policy, all compromise the certainty of carbon storage, as much as that of timber production values. No-one can guarantee that carbon locked up by forests will remain so for ever, even if this is the plan.

Thus, in addition to the effect of discounting, future carbon values are reduced by these and other threats.

Risk has sometimes been treated, especially in financial markets, by adding a premium to the discount rate. In relation to physical threats to forests' survival, such a treatment is widely regarded as crude at best and at worst (in relation to future costs) systematically perverse (Price 1993, Chap. 11). Technically, risk is distinguished from uncertainty in that the probability distribution of possible outcomes is known. If this is the case, then the appropriate treatment is to take a range of possible outcomes and to combine their probability-weighted values in a mean expected value. This approach can be applied as readily to carbon flux figures as to the cash flow profiles associated with forestry options. Where future probability distributions are uncertain an alternative far simpler, if ad hoc, approach followed under several voluntary carbon standards (Valatin 2011b, Table 5, p. 14), including the Woodland Carbon Code, is to reduce the anticipated future abatement by a risk factor based upon past experience and expert judgement.

### 2.11 Forestry Options: Do They Offer a Limited Stock of Solutions?

While there is, world-wide, an area of land estimated at around 1,500 million hectares that might be afforested, even a massive afforestation programme would only sequester at most a few decades' emissions at current levels (see Mahli et al. 2002). That is a much shorter period than the limit imposed by availability of fossil fuels. Thus carbon sequestration in forest biomass at maximum represents only a medium-term solution to the problems of accumulating atmospheric $CO_2$ and climate change. Accumulation in forest soils may continue for longer, but itself is likely to rise to an asymptotic limit. By contrast the abatement benefits of biomass energy and structural displacement are cumulative over successive cycles of harvesting and regrowth, so have a role to play in climate change abatement over the longer term.

Moreover, as an afforestation strategy proceeded, it is likely that progressively more costly options would have to be adopted. Thus invitations to offset emissions (for example by paying for some afforestation, as offered by airlines) are accompanied by figures that omit the long-term costs entailed for later offsetters, because of the earlier withdrawal of the cheapest options (cf. Price (1984) on the cost of depleting mineral resources).

If the carbon fluxes do not include revolatilisation, then the costs of climate change mitigation must include those of perpetuating forest cover, or of achieving a different, permanent solution to the climate change problem.

## 3 Reviews of Previous Studies

### 3.1 UK Studies

The earliest published UK study of climate change mitigation cost may be that of Price (1990), who compared the cost of mitigating $CO_2$ concentration by growing biomass for displacement use in power generation, with that of using trees to sequester $CO_2$ emissions from fossil-fuel-based generation. It introduced the discounted net cost per discounted flux unit approach and applied it to a forest plantation of typical species and productivity for the UK. Its assumptions were very basic: a uniform rate of sequestration was used during growth and, for the $CO_2$ sequestering option, the carbon in timber was assumed to be permanently fixed. No revenues from sale of timber were included. Applying a 7 % discount rate to a representative north-temperate zone afforestation scheme gave a cost per tonne *coal* of £356 for growing wood fuel and of £76 for sequestering the $CO_2$ emitted by burning a tonne of coal.

The approach of Price and Willis (1993) refined this technique, deriving carbon fixing profiles from yield models, and carbon volatilisation from decay rates specific to wood product groups. Some illustrative results from the approach appear as the

**Table 1** Some possible approaches to deriving marginal abatement costs in forestry

| Discount carbon[a] | Use irregular carbon uptake profile[b] | Include all future revolatilisation[c] | Include displacement of fossil-carbon - intensive materials and energy production | Cost of $CO_2$ abatement[d] £/tonne |
|---|---|---|---|---|
| No | Immaterial | No | No | £2,913/463 tonnes = 6.3 |
| Yes | No | No | No | £2,913 annualised/9.28 tonnes/year = 13.4[e] |
| Yes | Yes | No | No | 18.0[f] |
| Yes | Yes | Yes | No | 31.4[f] |
| Yes | Yes | Instant volatilisation | No | 38.5[f] |
| Yes | Yes | Yes | Yes | 19.4[f] |

[a]Where carbon fluxes are discounted, an illustrative 3.5 % rate is used
[b]Irregular carbon uptake is according to the Forestry Commission yield model for thinned Sitka spruce yield class 12 (Edwards and Christie 1981)
[c]Volatilisation is at rates given by Thompson and Matthews (1989)
[d]In the absence of agreed figures, a notional figure only is used for the effect of displacement, it being taken to have similar magnitude to the direct lock-up of carbon in the timber
[e]An annuity (calculated at 3.5 %), equivalent to £2,913 over the rotation is divided by the mean annual $CO_2$ fixed (i.e. 9.28 $tCO_2$)
[f]Breakeven price

bottom four rows of Table 1. The paper also estimated the area of forest that would need to be planted (2.3 ha) to mitigate the $CO_2$ emissions associated with an international forestry conference.

A recent review of three studies estimating the climate change mitigation cost-effectiveness of UK forestry measures (Radov et al. 2007; Moran et al. 2008; ADAS forthcoming – results from the latter are also published in Matthews and Broadmeadow 2009) illustrates differences of approach in some recent studies (Valatin 2012). Estimates from the three studies, together with some of the underpinning assumptions, are summarised in Table 2.

Note that the Radov et al. (2007) estimates and some of those in ADAS (forthcoming) are of the same order of magnitude as those calculated by the discounted carbon flux approach of Price and Willis (1993) shown in the bottom four rows of Table 1. However, differences in method between all the studies preclude over-arching conclusions from them about the relative cost-effectiveness of different forestry measures.

More recently, reporting large variations in land values between regions and grades of agricultural land, Nijnik et al. (2013) illustrate how abatement cost estimates tend to increase on higher quality agricultural land. Cost estimates reported for Scotland ranged from £4/$tCO_2$ (£15/tC) for Sitka spruce yield class 16 planted on poor quality uncultivated agricultural land previously used for livestock, to £21/$tCO_2$ (£76/tC) where prime arable land instead is used (Nijnik et al. 2013, Fig. 2, p. 39). Due to regional differences in opportunity costs and in timber prices, estimates also vary across the UK. Estimates for Sitka spruce yield class 12 planted on 'grade 3'

**Table 2** Cost-effectiveness of UK forestry measures

| | Radov et al. (2007) | Moran et al. (2008) | ADAS (forthcoming) |
|---|---|---|---|
| Time period(s) covered | (i) 2009–2012<br>(ii) 2009–2017<br>(iii) 2009–2022 | to 2022 | (i) to 2022<br>(ii) to 2050 |
| Baseline land use | Arable | Sheep | Rough grazing/uncultivated |
| Carbon pools covered | T, S | T, L and S | T, L, S and HWP |
| Carbon benefits covered | Seq | (a) Seq<br>(b) SeqSbm<br>(c) SeqSbf | (a) Seq<br>(b) SeqSbm(m)<br>(c) SeqSbm(h) |
| Tree species and yield class options considered | 2 | 1 | 14 |
| Opportunity cost (£/ha/year) | £120 to £148[a] | £141 | £50 to £350 |
| Loss in land value (£/ha) | £2,500 to £7,500[a] | Not included separately | Not included separately |
| Establishment cost(s) (£/ha) | £1,250 to £3,000 | £1,250 | £1,310 to £5,400 |
| Timber price profile | n.a. | 2.5 % annual increase | 2 % annual increase |
| Discount rate applied | 7 % | 3.5 % | 3.5 % |
| Woodland creation cost-effectiveness (£/t$CO_2$e) | ~£20 to ~£40 | (a) −£7<br>(b) −£2<br>(c) −£6 | (a) −£61 to £103<br>(b) −£61 to £73 |
| Forestry management cost-effectiveness (£/t$CO_2$e) | Not considered | (a) £1<br>(b) £12[b] | (a) −£52[c] |

Notes: Carbon pools: T: Tree; L: litter; S: Soil; HWP: harvested wood products; Carbon benefits: Seq carbon sequestration; SeqSbm carbon sequestration and materials substitution; (m) 'medium' materials substitution; (h) 'high' materials substitution benefits; SeqSbf carbon sequestration and fossil fuel substitution benefits in energy generation; Seqd carbon sequestration and displacement (including carbon storage in harvested wood products and fossil fuel substitution benefits in materials and energy generation)

[a]There may be an element of double-counting here (an issue not discussed in Radov et al. 2007).

[b]Assumes shortened rotation length (59 years to 49 years)

[c]Assumes increased management of currently under-managed woodland; Cost-effectiveness not estimated for medium substitution benefits or carbon sequestration alone due to apparent negative abatement potential

livestock land are reported to range from £7/t$CO_2$ (£27/tC) in Scotland to £17/t$CO_2$ (£65/tC) in south-east England (Nijnik et al. 2013, Fig. 3, p. 39). In general abatement costs are argued to be highest where land prices are greatest due to the stronger effect of land price differentials than of timber price ones (land prices and timber prices both tending to be higher in England than Scotland). The analysis does not account for differences in carbon displacement or ancillary (e.g. recreation and amenity) benefits, however: these could affect the ranking of options.

In each case the estimates in these studies generally suggest that forestry measures are cost-effective relative to social values of carbon recommended by the UK government for policy appraisal based upon the cost of meeting national

abatement targets (Valatin 2011b). These social values include a central estimate for 2012 of £58/t$CO_2$e for 'non-traded' sectors (not part of the EU emissions trading scheme) at 2012 prices, rising over time to a peak of £334 per t$CO_2$e in 2077, declining thereafter (HM Treasury and DECC 2012, supporting Table 3). However, direct comparison of estimates in the table above is hampered by differing approaches, lack of clarity about the precise methodology in some cases, and the fact that the options are not generally alternatives for particular areas of land (Valatin 2012).

None of the three studies include ancillary benefits. More recent studies that have made climate change cost-effectiveness estimates while embracing ancillary benefits include Nisbet et al. (2011) and Valatin and Saraev (2012). The first of these focuses primarily upon benefits of woodland planting for flood risk reduction in the catchment upstream of Pickering, Yorkshire, but also covers habitat creation and erosion prevention benefits, while the second includes health and amenity benefits associated with woodland planting in Wales. As expected, inclusion of ancillary benefits improves the estimated cost-effectiveness of the forestry options. Although coverage of ancillary benefits is partial and differs, the studies otherwise adopt a similar approach based closely upon that recommended in UK government guidelines (DECC and HM Treasury 2011) and the approach to accounting for non-permanence adopted under the Woodland Carbon Code (Forestry Commission 2011a). Nisbet et al. (2011) report indicative cost-effectiveness estimates ranging from −£62/t$CO_2$ to £3/t$CO_2$, while Valatin and Saraev (2012) report estimates ranging from −£37/t$CO_2$ to £13/t$CO_2$. In both studies, the woodland creation options considered are judged highly cost-effective as climate change mitigation measures under the DECC and HM Treasury (2011) approach (although this is not the primary purpose of woodland creation in the first case).

By contrast to these results, evaluations which include non-market disbenefits, such as the effect on the landscape of large-scale clear-felling at the end of commercial rotations, would increase the associated social cost/t$CO_2$e. Potential lost hydroelectricity generation through afforestation may be of particular concern to the extent that its consequences include more electricity generation using fossil fuels (Barrow et al. 1986). The severity of impact on HEP, however, may be reduced by application of current practices and guidelines on forestry and watercourses (Nisbet 2005; Forestry Commission 2011b, requirement 74, p. 40).

## *3.2 International Studies of Forestry Mitigation Costs*

The very low cost, equivalent to about \$2/t$CO_2$, for the forest-based carbon sequestering option given by Sedjo and Solomon (1989) may result from the non-discounting of carbon fluxes, and a low opportunity cost of land, issues which also affect the \$3/t$CO_2$ estimate of Sedjo and Ley (1997), and remain to this day.

An early study of change *within* forestry suggested a cost of \$4 to \$7/t$CO_2$ (depending on discount rate) for a limited modification of regional silviculture to enhance carbon fixing (Hoen and Solberg, 1994).

Healey et al. (2000) calculated the break-even price for a tonne of carbon flux, for a project defined as converting an area of conventional logging to one of reduced impact logging (RIL). The study included some ancillary benefits of RIL, to biodiversity and water quality: these were deducted from the net cost of conversion to RIL in deriving the break-even price. This ranged from \$0 to 12/t$CO_2$.

Richards and Stokes (2004) give a range of \$10 to \$150 per tonne of carbon (equivalent to \$3 to \$41/t$CO_2$) but note the difficulties of making comparisons between studies, because of the different units, approaches and assumptions used, as we have discussed above.

Many more recent international studies suggest that forestry options are relatively inexpensive. Stern (2006), for example, notes that a substantial body of evidence suggests that preventing further deforestation would be relatively cheap, while Sohngen (2009) argues that forestry options could halve the total cost of abatement required to meet the 2 °C threshold target. Costs vary greatly between settings, with a range of \$3 to \$280/t$CO_2$ given by van Kooten and Sohngen (2007). Estimates from 'bottom-up' studies suggest that forestry can offer abatement of around 6 Gt$CO_2$e/year in 2030 at a cost of less than \$100/t$CO_2$e, just over half of this at under \$50/t$CO_2$e (IPCC 2007a, Fig. 4.2, p. 59).

To a considerable extent, this view – that forestry offers relatively inexpensive mitigation – is vindicated by comparison with other figures for carbon price mentioned below.

## *3.3 Other Approaches to Carbon Pricing*

Comparative studies are a focus for government evaluations of marginal abatement costs. The relative cost-effectiveness of the many potential forestry options should be set in a context of other means of mitigating climate change, and the economic appraisal thereof. An early classification of economic approaches (Price and Willis 1993) recognised eight general methods for pricing carbon (including via cost of carbon sequestration by woodlands and other ecosystems). Even at this time a huge range of prices was quoted (Table 3).

Some of these alternative approaches to pricing carbon, with further illustrative figures where they have been found, are discussed below.

### Other Means of Reducing $CO_2$ Concentrations

Alternative mitigation options under review include geo-engineering, which is defined by IPCC (2012, p. 2) as 'a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change'. They also include means of physically storing $CO_2$ out of the atmosphere–ocean system, reducing the $CO_2$ intensity of energy production, and reducing energy consumption. IPCC (2007b, pp. 78–79) were cautious about the scope and cost of

**Table 3** Methods of pricing $CO_2$: an early survey

| Flux pricing method | Time-scale | Example of exponents at that time | Cost/$tCO_2e$ |
|---|---|---|---|
| 1. Constraint on growth of $CO_2$ emissions bottom-up | Phased | National Academy of Sciences (1991) | £0 to £65 |
| 2. Constraint on growth of $CO_2$ emissions top-down | Phased | Jorgensen and Wilcoxen (1990) | £1 to £8 |
| 3. Extra cost of low carbon fuel | Instant | Price (1990) | £97 |
| 4. Extra cost of low carbon fuel: delayed and discounted | Future | Anderson (1991) | £7 |
| 5. Cost of sequestering carbon (as discussed above) | Prolonged? | Sedjo and Solomon (1989) | £2 |
| 6. Cost of altering radiative balance | Prolonged? | National Academy of Sciences (1991) | Trivial? |
| 7. Lost production, damage cost and defensive spending | Perpetual | Nordhaus (1991), Cline (1992) | 5p to £25 |
| 8. Carbon tax to achieve target | Undefined | Cline (1992) | £18 to £49 |

Note: these prices were compiled in 1993, and reflating them to 2012 prices would imply that they can probably be more or less doubled now. For purposes of comparison, prices originally given in £/tC have been converted to £/$tCO_2e$

some of these options: 'geo-engineering solutions to the enhanced greenhouse effect have been proposed. However, options to remove $CO_2$ directly from the air, for example, by iron fertilization of the oceans, or to block sunlight, remain largely speculative and may have a risk of unknown side effects. … Detailed cost estimates for these options have not been published and they are without a clear institutional framework for implementation.' Schellnhuber (2011) notes that carbon sequestration through industrial 'air capture' could well cost of the order of \$1,000/$tCO_2$.

## Sequestering by Other Means

Other biological processes of sequestering carbon apart from by growing trees, such as photosynthesis by phytoplankton, seaweed and other types of marine algae, or accumulation of peat or biochar, may also add to carbon stocks. Intervention to accelerate the processes is more problematic, and little attention seems to have been given to providing a comprehensive account of their potential to enhance climate change mitigation on a significant scale. Some indicative estimates are available. For example, Moxey (2011) suggests indicative costs of restoring degraded peatlands through grip blocking in order to restore them to $CO_2$ sinks from their current position as $CO_2$ sources (resulting from previously being drained, etc.) may typically be around £13/$tCO_2$ (see also Artz et al. 2012). However, the authors are not aware of any large-scale and well-agreed costings of these sequestration strategies (and would welcome information on such costings). This may be partly due to the present scarcity of evidence on associated carbon fluxes, although these

are the focus of ongoing research – including some related to interests in the UK (e.g. Duke et al. 2012) – in developing a Peatland Carbon Code. (For a review of current evidence on carbon fluxes and GHG emissions associated with UK peatlands, for example, see Worrall et al. (2011)).

IPCC (2005) give a range of costs for carbon capture and storage of $CO_2$ emissions, particularly from power plant, from \$0 to \$270/t$CO_2$. Pöyry Energy Consulting (2007) estimate that in the UK some carbon capture and storage at power stations could be achieved at a cost below £25/t$CO_2$, but note that there is limited scope at this price. Storage in aquifers and oil-fields seems also susceptible to the kind of long-term risk that attends forestry options.

Biogeological processes have of course been responsible for reducing atmospheric $CO_2$ to a level at which present terrestrial life is possible, by incorporation in limestone and other carbonate rocks derived from animal skeletons and through chemical precipitation. However, these processes have taken hundreds of millions of years to sequester the existing amount of carbon. While human action to accelerate the processes is conceivable, it may seem hardly conceivable that this could take place on a short enough time scale to meet present targets. Schuiling (2012) does argue that this approach is feasible by spreading crushed olivine (involving enhanced weathering of crushed magnesium silicates) at a modest cost of around \$10/t$CO_2$. However, Schellnhuber (2012) advises caution about such 'silver bullet' solutions, noting their possible externalities (e.g. river acidification) and the associated cost.

This is not to say that none of these strategies could play a part in long-term solutions to climate change problems, but that in the present state of knowledge they cannot be relied upon to supply the needed quick solution, much less at a known, agreed and reasonable cost.

### Reduced $CO_2$ Intensity in Energy, Materials and Services Production

Existing final products and services might be made available to consumers through using more energy-efficient technologies, generating less $CO_2$ per unit of product. At the production end, there have been thermal efficiency increases for conventional thermal power generation, and in iron and steel making and other metallurgical processes. However, these gains are partly offset by the reduced quality of available fossil energy resources, such as shale oil: this entails heavier $CO_2$ overheads resulting from fossil fuel use in exploration and exploitation. There are thermodynamic limitations on how energy-efficient processes can become, and some necessarily entail a given quantum of $CO_2$ release that can only be avoided by reliable carbon capture and storage. Although until recently this was thought to be the case for cement production from limestone ($CaCO_3$), Berger (2012) reports that a process is currently being developed that does not give rise to carbon dioxide emissions – instead producing lime, graphite and oxygen. However, this uses solar energy that could otherwise displace fossil-fuel-based energy production, and thereby affects $CO_2$ emissions indirectly. Lighter, more material-parsimonious structures also offer further savings.

At the consumer end, there are more energy-efficient cars, electrical appliances and light bulbs; and, more radically, change of transport mode from private to public with its further advantages of reducing congestion.

As well as by saving energy input, $CO_2$ emissions can be reduced by varying the mix of energy-generation technologies including renewables such as photo-voltaics, wind, hydroelectric power and waves. (Tidal energy, often included as a renewable, is technically a depleting stock resource, derived from the rotational energy of the Earth. However, rough estimation shows that the rotational energy of the earth is equivalent to hundreds of millions of years of current global energy consumption – it's amazing how much energy can be stored in a large, rapidly rotating flywheel!) Nuclear power, like all forms of electricity generation, entails GHG emissions during construction and operating phases, and also in uranium mining. Concerns about safety, augmented by major releases of radioactive pollution and the loss of life in accidents over the past 25 years, caused fresh capacity to be dropped from the future energy portfolio of some countries (e.g. Germany and, at least initially, Japan). A perception that these problems are not serious compared with those of climate change has led some to favour its reintroduction, but the concerns themselves generally remain unalleviated.

For an illustrative cost of renewables, consider a photo-voltaic system with an ascribed economic life of 40 years. Using installation cost, estimated generation figures and $CO_2$ saving for the system supplied by EvoEnergy (personal communication), and current prices of imported and exported electricity, the costs are:

- With 10 % discount rates, £576/t$CO_2$
- With 3 % discount rates, £147/t$CO_2$
- With 3 % rate for cash and 1 % for carbon, £105/t$CO_2$
- With 1 % rates, £51/t$CO_2$

At low discount rates, cost is sensitive to project life. With 55-year life and 1 % rates, the project breaks even and abatement is "free".

It would be expected that, with scale economies, a commercial installation using this technology would also provide free abatement, vindicating Anderson's speculation in 1991 that costs of low-carbon energy would fall dramatically.

These and technologies like them are in the end the ones that must be deployed to deal with the twin problems of $CO_2$ accumulation and depletion of fossil energy. Realistically, afforestation, reforestation and other biological $CO_2$ mitigation options do not provide more than a medium-term, 'holding' solution, to give time while these technologies' competence is evolved to a low enough cost, on a sufficient scale. In the meantime, each tonne of carbon prevented from entering the atmosphere as $CO_2$ has a cost which can be measured in essentially the same format (calculating £/t$CO_2$e) that would be used in appraising the cost-effectiveness of physical and biological systems for carbon sequestration. However, where a measure increases consumers' disposable income because it reduces their energy bills, only GHG savings net of the direct 'rebound effect' (associated increases in consumption of the main energy service in question) are accounted for under current UK government guidelines in valuing changes in energy use (HM Treasury and DECC 2012, pp. 17–19).

The premium willingly paid for current modes of transport and for current modes of production and consumption might be taken as reflecting their value over-and-above that of the low $CO_2$ modes. But such premia also reflect the inertia of technology and consumption patterns: the exigencies of climate change might prove a valuable incentive to adopt technologies that might be superior, irrespective of their impact on climate. The classic case, originally driven by energy conservation considerations, is the low-energy light bulb, which provided at first a win–win saving in energy and in electricity bills, and now offers a mandatory win–win–win–win change, with saved $CO_2$ emissions and reduced annual household investment cost added to the initially proclaimed benefits.

Low-energy refrigerators and tumble-dryers also offer rational investments in energy-saving to those already owning a model with high energy consumption, or choosing which model to buy, with $CO_2$ reduction benefits as a bonus. That these options are not taken up by consumers may reflect both a lack of knowledge of the benefits and a high discount on future energy savings (Gateley 1980).

### Reduced Consumption

Energy economy can be achieved just by reducing what we consume: fewer holidays abroad, fewer hours of television, more fastidious switching off of lights and appliances not in use. In conventional economic terms, the cost of lost consumption would be considered as the price of energy, being a measure of consumers' willingness to pay for its use (no matter how wasteful the use might be). The view of alternative economics might be that such reduced material consumption might in fact enrich lives and health, by forcing us back on human relationships and physical activity as a means of finding satisfaction.

A naive estimate of what would be implied for the value of lost consumption could be given by dividing GDP by current emissions, resulting in a loss of more than £2,500/t$CO_2$! However, this takes no account of a selective effect whereby the least valued consumption/t$CO_2$ would be sacrificed first. It also takes no account of ways in which energy consumption can be reduced without reducing consumption of final goods and services (see discussion above). More sophisticated approaches illustrated on the top two lines of Table 3 consider how the economy can best adjust to constrained $CO_2$ emissions, respectively by top-down economic optimisation and by bottom-up 'engineering' approaches. (For a discussion of implications for cost-effectiveness estimates of adopting a bottom-up 'engineering', a sectoral optimisation, or an econometric modelling approach, see Dempsey et al. (2010)).

## Other Means of Mitigating Climate Change

Among the options that seek to mitigate the effect of climate change other-than-by slowing or reversing $CO_2$ accumulation in the atmosphere, there is altering the radiative balance by circling the earth with a belt of 'smart mirrors' launched by rocket.

This would replicate the effect of industrial smoke and volcanic particulates in the upper atmosphere, which reflect back solar radiation, and have been responsible for the so-called 'global dimming effect', as a result of which it is estimated that the globe has warmed by 0.6 °C less than the present levels of GHGs would indicate (Hansen et al. 2005). NASA (quoted in Cline (1992)) once reported the cost of launching smart mirrors as 'trivial', but perhaps that should be interpreted in the context of an agency whose annual budget has been about $18 billion in recent years (Office of Management and Budget various years), and does not account for potential negative impacts.

More recently, injection of sulphate particles into the stratosphere has become the focus of such discussions. Crutzen (2006) suggests that the cost of 'injections to counteract effects of doubling $CO_2$ concentrations would be $25 to 50 billion a year.' Keith et al. (2010) claim that 'This is over 100 times cheaper than producing the same temperature change by reducing $CO_2$ emissions.' While implicitly less costly than $CO_2$ mitigation measures, no equivalent cost/t$CO_2$ was given. But problems of delivery, side-effects, and the short duration of the effect have been raised by Robock et al. (2009). Furthermore, IPCC (2012, p. 5) note that existing studies of the costs of solar radiation management methods are 'limited primarily to implementation (direct) costs, and even then there is limited literature for even the most prominent techniques; indirect costs and possible impacts are poorly explored, particularly in relative comparisons against ongoing climate change.' (See also discussion in Royal Society (2009) and Schellnhuber (2011)).

### Business-As-Usual: The Social Cost of Climate Change

The laissez-faire option (method 7 in Table 3) was formerly favoured as the complete solution by climate change sceptics (Bate and Morris 1994). Many economists (e.g. Nordhaus 1993, 2007) consider it as one of a suite of options to be evaluated. It entails accepting the consequences – if any – of business-as-usual conduct of the world economy. If there are adverse effects – which the great majority of scientists now consider highly likely – then those can be subject to economic valuation. In a rational appraisal, the question is whether the cost of those adverse effects is greater than the cost of mitigating them, and if so how far the mitigation measures should go. In recent years, authoritative commentators have come to markedly different conclusions on this matter (Stern 2006; Nordhaus 2007). Note also that ethical issues discussed in section "The Case for Not Discounting Carbon Fluxes" imply that trade-offs are not always considered to apply (e.g. to the extent that preferences for avoiding significant harms are lexicographic).

The economic cost of *not* mitigating the effects of $CO_2$ accumulation, consequent climate change and sea-level rise can be interpreted through: the forgone benefits of a less productive global economy; the disbenefits such as poorer health; the costs of defensive measures such as sea-wall and flood defences and temperature amelioration and health protection; and those of 'retreat' from lands which it is deemed too expensive to defend.

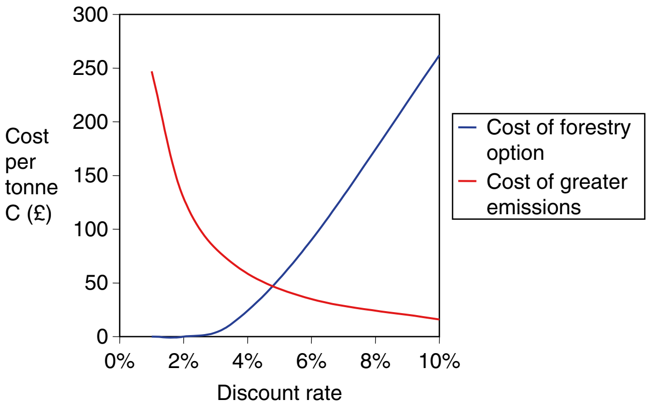


**Fig. 1** Cost of mitigation versus cost of business-as-usual. Notes: The cost is per tC, not per $tCO_2$; The indicative cost of greater emissions has been calculated under reasonable assumptions about the relationships among $CO_2$ concentrations, rates of $CO_2$ uptake, temperature change, thermal inertia and economic damage. While sensitive to these assumptions, the relationship between discount rate and cost per tonne of carbon always shows this rising path. Source: Presentations made by Colin Price at various seminars in 2010

Some of the many problems of evaluating the costs of continuing emissions are:

- Rates of uptake and equilibrium levels in oceanic and terrestrial sinks;
- Relationships between $CO_2$ levels and temperature change;
- Rates of temperature adjustment given the thermal inertia imparted largely by the oceans;
- Mapping from temperature rise to economic damage;
- Nonlinearities in the above relationships; especially
- Threshold effects; and
- Positive feedbacks;
- Discounting, as discussed above.

All these mean that the effect of another $tCO_2$ does not have a simple, predictable cost. The uncertainty and the precautionary principle have led to reduced willingness to accept the business-as-usual approach, with costings increasingly erring on the side of caution.

Early figures quoted in the literature included \$5/tC (Nordhaus 1993) and \$20/tC (Fankhauser 1995). Clarkson and Deyes (2002) from an international survey report a range from \$9 to \$197/tC, equivalent to £2 to £34/$tCO_2$ at the present exchange rate of £1 = \$1.60, and give a preferred figure equivalent to £19/$tCO_2$. Stern (2006) focuses on costs of global scenarios, but uses a cost of \$85/$tCO_2$ under a business-as-usual scenario, acknowledging that this lies above typical figures in the literature, but pointing out that the figure falls well within the range of quoted figures, and that it takes account of risks explicitly.

Comparison of cost of mitigation, by a representative upland afforestation option in the UK, with the option of bearing climate change shows, as might be expected, acute sensitivity to discount rate, as Fig. 1 demonstrates. The higher the discount rate, the smaller the significance of long-drawn-out forest sequestration,

**Table 4** Some prices in carbon markets

| Source | Date | Price per tonne CO² |
|---|---|---|
| Biocarbon Fund | 2003 | $3 |
| Den Elzen and de Moor | 2002 | $4.5 to $5.5 |
| International Emissions Trading Association | 2003 | $9.9 to $13.7 |
| Grubb | 2003 | $9 to $22 |
| PointCarbon | 2008 | $35 |

Source: Olschewski and Benitez (2010)

so the higher the cost per unit sequestered. On the other hand, the higher the discount rate, the smaller the significance of long-term climate change, so the *lower* the cost per unit emitted. Although the costs of climate change are also subject to significant uncertainty and their quantification is not uncontroversial (as noted above), it is noteworthy that Fig. 1 implies that the switching point between options occurs in the range of discount rates normally discussed in the academic literature and in commercial practice, but that the forestry option is cheaper than business-as-usual under the UK government's preferred range of discount rates of 3.5 % to 1 % (HM Treasury 2003).

## Market Prices

Those with a marketist predisposition might point out that markets already exist for carbon, giving a price by an approach additional to those recorded in Table 3. However, prices fluctuate dramatically through time and even vary across markets at a point in time (Table 4).

Since this table was compiled, there has been some downward pressure on prices, partly in response to the onstreaming of many forestry projects 'undertaken under REDD. Nevertheless, Peters-Stanley and Hamilton (2012) report a price increase in voluntary markets. Prices in forest carbon markets are also reported to have risen from $3.8/tCO_2$ in 2008 to $5.5/tCO_2$ in 2011 (see Diaz et al. 2011).

The more fundamental objections to using 'market' prices are that:

- There are no 'natural' free-market prices for carbon sequestration or emissions. What prices exist, are constructed prices, derived in response to governmental and intergovernmental regulations, stipulations and moral suasion, and selling to consumers what may be misguided 'warm glows' (Price in review); and
- The level of market prices, based upon demand from a relatively small section of the economy, does not account sufficiently for damage costs to society of emissions.

## Taxing to Achieve a Mitigation Target and Other Fiscal Measures

Road fuel tax in the UK amounts to around £250/$tCO_2$, though some such taxation has been in place since long before climate change became identified as a problem.

It has a mix of economic roles, in revenue raising, in funding transport infrastructure and in countering other externalities, such as those associated with congestion and road traffic accidents. Nowadays reduction of $CO_2$ emissions is a much-discussed and widely promulgated reason for such taxation. The absence of equivalent taxation of aviation fuel is seen by many as an anomaly that hampers achievement of emissions reductions, especially in an era of rapidly growing air travel.

The UK government presently offers a premium ‘feed-in tariff’ for solar-generated electricity, which might be taken to express its willingness to pay to meet an emissions reduction target. Each unit of electricity generated by thermal stations is associated with almost 0.5 kg $CO_2$ emission. The initial domestic feed-in tariff (FIT) of 43p per unit (kWh) therefore implied a valuation of abatement of around £800/$tCO_2$, and even the present values applying to new solar photovoltaic installed after August 2012, which range from 7p to 16p per unit (OFGEM 2012), imply a range of about £140/$tCO_2$ to £300/$tCO_2$. Rapid reduction in FIT suggests either that the falling cost of solar generation makes it easier to meet the target, or that the price is now seen as too generous.

Fiscal measures required to meet a standard may not always be an independent assessment of the price of $CO_2$ emissions, if the standards are set as a result of perceived costs of emissions, among other factors. Using these measures as a price then risks running into circular arguments.

## 4 Discussion and Conclusions

Climate change mitigation is considered by many governments and international agencies to constitute the greatest challenge currently facing humanity. The task is urgent if international aspirations to prevent ‘dangerous’ climate change are to be met, with the International Energy Agency’s Chief Economist warning that’… the door to 2° – which is a must for a decent life – is closing forever‘(IEA 2011; see also Peters et al. 2013).

Price Waterhouse Cooper (2012) have also concluded that the current global rate of $CO_2$ emissions reduction (0.7 % per year) is very far short of that required (5.1 % per year) to limit temperature change to 2 °C. They note too that reduction in US $CO_2$ emissions was partly achieved by switching to shale gas, and fear that the availability of this possibly short-term resource may reduce pressure to adopt renewable energy solutions. All this suggests an even greater urgency to adopt cost-effective options that can mitigate $CO_2$ levels in the medium term. Experience also suggests a case for front-loading emissions reductions rather than focusing upon meeting future targets (Latin 2012).

Forests potentially have a very important role to play globally in climate change mitigation. In the absence of mitigation efforts, current deforestation rates could make stabilisation of atmospheric GHG concentrations at a level that avoids the worst effects of climate change highly unlikely (Eliasch Review 2008). Afforestation and agroforestry options also provide a potential way of reducing existing

atmospheric GHG concentrations from levels considered by some scientists to be already too high. If the challenging international target of limiting temperature increase due to anthropogenic causes to a maximum of 2 °C (or possibly 1.5 °C) is to be met, realising the potential of forests to increase carbon sequestration and also for increased substitution through use of wood products will be critical. Because $CO_2$ emissions persist in the atmosphere – some part of them indefinitely – merely *reducing emissions* does not reduce $CO_2$ levels in the atmosphere. Moreover, because of the long lags of adjustment processes, the need to reduce net emissions is immediate: by the time critical temperature changes are approached, it will be too late for mitigating action to prevent their being exceeded. In temperate forestry, there is the further consideration that many years may elapse before an afforestation project reaches its fastest sequestration rate.

Both the amount of abatement by forestry and the potential contribution of each type of option depend upon the level of incentives (e.g. carbon prices). A primary reason that deforestation and forest degradation are currently large net sources of carbon emissions is that traditionally there has been little incentive for landowners or forest users to account for non-market values, including the social value of carbon sequestration and storage. Opportunities for climate change mitigation by forestry are being lost in the existing institutional structure (Nabuurs et al. 2007), although the situation is slowly changing as payment-for-ecosystem-services schemes develop, including markets for forest carbon, often underpinned by regulatory change and new institutions. At international level, some progress has been made in agreeing financing mechanisms for reduced emissions from deforestation and forest degradation (REDD and REDD+) following agreement at Bali (UNFCCC 2008). National initiatives are also developing, such as the launch in 2011 of a Woodland Carbon Code by the Forestry Commission (2011a) to help underpin an emerging market for carbon sequestration by UK woodlands.

There remain research gaps in the supporting evidence too. As noted above, for the UK these include robust evidence on impacts of afforestation on forest soil carbon balance. Other gaps include a paucity of comprehensive GHG balances for UK forest stands, carbon stock changes during early tree growth and once stands reach maturity, and carbon substitution (or displacement) benefits (Morison et al. 2012). Research on albedo, evapotranspiration and other biophysical factors, including the impact of surface roughness on exchanges of energy and mass between the land surface and the atmosphere, remains at an early stage (see Anderson et al. 2011). Better evidence is also needed on opportunity costs and on leakage effects.

There remain, too, unresolved issues in the appropriate means of calculating a mitigation cost, associated with the long time-span of forestry.

However, unresolved issues and the multiplicity of economic and biophysical factors involved do not mean, as some argue (e.g. van Kooten et al. 2012), that the abatement benefits of forestry options are currently too uncertain to estimate.

Despite the lack of internationally accepted approaches at present, as noted above, available evidence indicates that forestry options are relatively cost-effective compared with a range of alternatives. Whether this conclusion holds in particular

cases could be expected to vary between projects and regions, as well as being dependent upon the approach adopted. To the extent that the cost-effectiveness of forestry options depends upon the methodology adopted and benchmark used, future comparisons could benefit from greater methodological transparency and consistency. Lack of transparent methodology has been raised as a particular concern with some previous studies (e.g. see Kesicki 2011; Ekins et al. 2011).

Recent studies in the UK suggest that some forestry options are generally very cost-effective judged by current UK government benchmarks. Accelerating global emissions, impacts that are possibly more severe than anticipated, non-negligible probabilities of catastrophic impacts, and a desire for greater certainty that critical thresholds will not be exceeded, might lead to adoption of tighter abatement targets. If so, estimates of the social value of carbon would need to be revised upwards (Valatin 2011b). This would make forestry options even more cost-effective compared with the social value of carbon.

However, the main point to stress is not that forestry options are relatively cost-effective (although this is what the available evidence suggests), but that they will be critical if international objectives on climate change mitigation are to be met.

Reaching the climate change mitigation targets agreed at international level is challenging, but not impossible (Schellnhuber 2008; Den Elzen et al. 2010; Höhne et al. 2012; Peters et al. 2013), with a key issue being the cost entailed (e.g. Schellnhuber 2011). From a theoretical perspective, work on international environmental agreements (Valatin 2005) suggests that ‘free rider’ problems entailed in reaching a binding agreement may not be as significant a barrier as early work by economists and game theorists had suggested, with challenges relating more to coordination issues, including fairness and justice. (Subsequent work on minimum participation rules confirm the underlying results – see Carraro et al. (2009) and Weikard et al. (2009).) On a practical level, sources of disagreement include whether an agreement should be based upon equal per capita emissions (e.g. Chang 2012), or some other measure, perhaps related to needs, resources available, or historic responsibilities for causing the rises in atmospheric GHGs. They also relate to whether it should be based upon countries’ ‘carbon footprint’ in terms of domestic consumption, or upon emissions due to domestic production (see Helm (2012a, b) who refers to evidence that emissions from production fell by 15 % in Europe over the period 1990–2005, but increased by 19 % in terms of consumption). Beyond these matters for negotiation, scope exists too for action by individual countries, that could potentially lead to the targets’ being met, even in the absence of a strong global agreement. For example, Helm et al. (2012) argue that introduction of border carbon adjustments would provide incentives for subsequent adoption of similar measures by other countries, along similar lines to the most likely outcome of the current dispute between the EU and other countries over inclusion of aviation under the EU ETS.

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## References

ADAS (forthcoming) Analysis of policy instruments for reducing greenhouse gas emissions from agriculture, forestry and land management – forestry options. Report to Forestry Commission England, ADAS, Abingdon, Oxfordshire. (Final draft versions dated June 2009 and July 2011)

Adger N, Fankhauser S (1993) Economic analysis of the greenhouse effect: optimal abatement level and strategies for mitigation. Int J Environ Pollut 3:104–119

Anderson D (1991) The forestry industry and the greenhouse effect. Scottish Forestry Trust and Forestry Commission, Edinburgh

Anderson R, Canadell J, Randerson J, Jackson R, Hungate B, Baldocchi D, Ban-Weiss G, Bonan G, Caldiera K, Cao L, Diffenbaugh N, Gurney K, Kueppers L, Law B, Luyssaert S, O'Halloran T (2011) Biophysical considerations in forestry for climate protection. Front Ecol Environ 9(3):174–182

Artz R, Donnelly D, Cuthbert A, Evans C, Smart S, Reed M, Kenter J, Clark J (2012) Restoration of lowland raised bogs in Scotland: emissions savings and the implications of a changing climate on lowland raised bog condition. IUCN/James Hutton Institute/ Scottish Wildlife Trust/Esmée Fairburn Foundation

Arvizu D, Bruckner T, Chum H, Edenhofer O, Estefen S, Faaij A, Fischedick M, Hansen G, Hiriart G, Hohmeyer O, Hollands K, Huckerby J, Kadner S, Killingtveit Å, Kumar A, Lewis A, Lucon O, Matschoss P, Maurice L, Mirza M, Mitchell C, Moomaw W, Moreira J, Nilsson L, Nyboer J, Pichs-Madruga R, Sathaye J, Sawin J, Schaeffer R, Schei T, Schlömer S, Seyboth K, Sims R, Sinden G, Sokona Y, von Stechow C, Steckel J, Verbruggen A, Wiser R, Yamba F, Zwickel T (2011) Technical summary. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlomer S and von Stechow C (eds) (2012) Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change. Cambridge University Press. http://www.ipcc.ch/pdf/special-reports/srren/SRREN_Full_Report.pdf. Accessed 5 Mar 2013

Ayers R, Walter J (1991) The greenhouse effect: damages, costs and abatement. Environ Resour Econ 1:237–270

Barrow P, Hinsley AP, Price C (1986) The effect of afforestation on hydroelectricity generation: a quantitative assessment. Land Use Policy 3:141–151

Bate R, Morris J (1994) Global warming: apocalypse or hot air? Institute of Economic Affairs, London

Berger M (2012) Solar-powered cement production without carbon dioxide emissions. Nanowerk. http://www.nanowerk.com/spotlight/spotid=24883.php. Accessed 12 Nov 2012

Brainard J, Bateman IJ, Lovett AA (2009) The social value of carbon sequestered in Great Britain's woodlands. Ecol Econ 68:1257–1267

Broadmeadow M, Matthews R (2003) Forests, carbon and climate change: the UK contribution. Information Note 48, Forestry Commission

Broome J (1992) Counting the cost of global warming. White Horse Press, Cambridge

Brown K, Cardenas L, MacCarthy J, Murrells T, Pang Y, Passant N, Thistlethwaite G, Thomson A, Webb N, with contributions from Dore C, Gilhespy S, Goodwin J, Hallsworth S, Hobson M, Manning A, Martinez C, Matthews R, Misselbrook T, Thomas J, Walker C, Walker H, Watterson JD (2012) UK greenhouse gas inventory, 1990–2010: Annual Report for Submission under the Framework Convention on Climate Change, AEA Technology report to DECC. http://naei.defra.gov.uk/reports.php?list=GHG

Caney S (2010) Human rights, climate change and discounting. In: O'Brien K, St Clair AL, Kristoffersen B (eds) Climate change, ethics and human security. Cambridge University Press, Cambridge, UK, pp 113–130, Chapter 7

Cannell MGR, Dewar RC, Pyatt DG (1993) Conifer plantations on drained peatlands in Britain: a net gain or loss of carbon? Forestry 66:353–369

Carraro C, Macrchiori C, Oreffice S (2009) Endogenous minimum participation in international environmental treaties. Environ Resource Econ 42:411–425

Chang SJ (2012) Solving the problem of carbon dioxide emissions. Paper presented at the IUFRO conference on new frontiers in forest economics, Zurich, June, 26th–30th. http://neffe.ch/index.php?id=48#c205. Accessed 15 Nov 2012

Clarkson R, Deyes K (2002) Estimating the social cost of carbon emissions. Government Economic Service Working Paper 140. HM Treasury/Defra, London

Cline WR (1992) The economics of global warming. Institute for International Economics, Washington, DC

$CO_2$Now (2013) Annual data: atmospheric $CO_2$. $CO_2$now.com website, http://co2now.org/. Accessed 31 Jan 2013

Crutzen PJ (2006) Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? Clim Change 77:211–220

Dasgupta PS, Heal G (1979) Economic theory and exhaustible resources. Cambridge University Press, Cambridge, UK

DECC and HM Treasury (2011) Valuation of energy use and greenhouse gas emissions for appraisal and evaluation. Department of Energy and Climate Change, London, http://www.decc.gov.uk/en/content/cms/statistics/analysts_group/analysts_group.aspx

DEFRA, DARDNI, RERAD, DRAH (2010) Agriculture in the United Kingdom. Department for the Environment, Food and Rural Affairs, London

Dempsey J, Plantinga A, Alig R (2010) What explains differences in the costs of carbon sequestration in forests? A review of alternative cost estimation methodologies. Chapter 4. In: Alig R (ed) Economic modeling of effects of climate change on the forest sector and mitigation options: a compendium of briefing papers. Report PNW-GTR-833, pacific North West Research Station. US Department of Agriculture, Corvallis, pp 87–108

Den Elzen M, Hare W, Höhne N, Levin K, Lowe J, Riahi K, Rogelj J, Sawin E, Taylor C, van Vuuren D, Ward M, Bosetti V, Chen C, Dellink R, Fenhann J, Gesteira C, Hanaoka T, Kainuma M, Kejun J, Massetti E, Matthews B, Olausson C, O'Neill B, Ranger N, Wagner F, Xiusheng Z (2010) The emissions gap report: are the Copenhagen pledges sufficient to limit global warming to 2°C or 1.5°C? UN Environmental Programme, Nairobi, www.unep.org/publications/ebooks/emissionsgapreport/. Accessed 5 Mar 2013

Department of the Environment (1991) Policy appraisal and the environment. HMSO, London

Dewar RC, Cannell MGR (1992) Carbon sequestration in the trees, products, litter and soils of forest plantations: an analysis using UK examples. Tree Physiol 11:49–71

Diaz D, Hamilton K, Peters-Stanley M (2011) State of the forest carbon markets 2011: from canopy to currency. Forest Trends, Washington, DC, http://www.forest-trends.org/publication_details.php?publicationID=2963

Dresner S, Ekins P, McGeevor K, Tomei J (2007) Forest and climate change: global understandings and possible responses. Chapter 6 in Freer-Smith P, Broadmeadow M, Lynch J (eds) Forests and Climate Change, Forest Research/CABI

Duke G, Dickie I, Juniper T, ten Kate K, Pieterse M, Rafiq M, Rayment M, Smith S, Voulvoulis N (2012) Opportunities for UK business that value and/or protect Nature's services; elaboration of proposals for potential business opportunities. Attachment 1 to Final Report to the Ecosystem Markets Task Force and Valuing Nature Network. GHK, London, http://uncsd.iisd.org/news/defra-reports-on-business-opportunities-in-protecting-nature%E2%80%99s-services/

Edwards PN, Christie JM (1981) Yield models for forest management. Forestry Commission Booklet 48. HMSO, Edinburgh, London

Ekins P, Kesicki F, Smith A (2011) Marginal abatement cost curves: a call for caution. Report to Greenpeace UK by UCL Energy Institute, University College London, London

Eliasch Review (2008) Climate change: financing Global Forests, independent report to government, commissioned by the Prime Minister and prepared by Johan Eliasch with the support of the Office of Climate Change, London

European Commission (2012) Climate action: emissions trading system (EU ETS). European commission. http://ec.europa.eu/clima/policies/ets/index_en.htm. Accessed 12 June 2012

FAO (2010) Global Forest Reseources Assessment 2010. Forestry Paper 163, UN Food and Agriculture Organization, Rome. http://www.fao.org/forestry/fra/fra2010/en/.Accessed 18 Dec 2012

Forestry Commission (2011a) The woodland carbon code. Version 1.3. Forestry Commission, Edinburgh
Forestry Commission (2011b) Forests and water UK forestry standard guidelines, 5th edn. Forestry Commission, Edinburgh
Forestry Commission (2012) Carbon leakage. Woodland carbon code section 3.3. Forestry Commission, Edinburgh, http://www.forestry.gov.uk/forestry/infd-8hngvh. Accessed 7 Nov 2012
Fankhauser S (1995) Valuing climate change. Earthscan, London
Gateley D (1980) Individual discount rates and the purchase and utilization of energy-using durables: comment. Bell J Econ 11:373–374
GCP (2012) Carbon budget and trends 2012. http://www.globalcarbonproject.org/carbonbudget/12/hl-full.htm. Accessed 31 Jan 2013
Gerlagh R, Liski M (2012) Carbon prices for the next thousand years. CESifo Working Paper 3855. http://re3.feem.it/getpage.aspx?id=4941
Gorte R (2009) Carbon sequestration in forests. Congressional research Service, Washington, DC, www.fas.org/sgp/crs/misc/RL31432.pdf
Hansen J, Nazarenko L, Ruedy R, Sato M, Willis J, Del Genio A, Koch D, Lacis A, Lo K, Menon S, Novakov T, Perlwitz J, Russell G, Schmidt GA, Tausnev N (2005) Earth's energy imbalance: confirmation and implications. Science 308:1431–1435
Hansen J, Sato M, Kharecha P, Beerling D, Berner R, Masson-Delmotte V, Pagani M, Raymo M, Royer DL, Zachos JC (2008) Target atmospheric $CO_2$: where should humanity aim? Open Atmos Sci J 2:217–231, http://pubs.giss.nasa.gov/cgi-bin/abstract.cgi?id=ha00410c
Healey JR, Price C, Tay J (2000) The cost of carbon retention by reduced impact logging. For Ecol Manage 139:237–255
Helm D (2012a) The carbon crunch: how we are getting climate change wrong – and how to fix it. Yale University Press, London
Helm D (2012b) Forget the Kyoto accord and tax carbon consumption. Environment 360. http://www.dieterhelm.co.uk/sites/default/files/YALEEnv360081112.pdf. Accessed 5 Mar 2013
Helm D, Hepburn C, Ruta G (2012) Trade, climate change and the political game theory of border carbon adjustments. Working Paper 80, Centre for climate change economics and policy, and Grantham research institute on climate change and the environment, Leeds/London. http://www2.lse.ac.uk/GranthamInstitute/publications/WorkingPapers/Abstracts/80-89/Trade-climate-change-border-carbon-adjustments-abstract.aspx. Accessed 15 Nov 2012
Henders S, Ostwald M (2012) Forest carbon leakage quantification methods and their suitability for assessing leakage in REDD. Forests 3:33–58, http://www.mdpi.com/1999-4907/3/1/33
Hepburn C, Koundouri P (2007) Recent advances in discounting: implications for forest economics. J For Econ 13:169–189
HM Treasury and DECC (2012) Valuation of energy use and Greenhouse Gas (GHG) emissions: supplementary guidance to the HM treasury green book on appraisal and evaluation in central government. HM Treasury and Department of Energy and Climate Change, London, https://whitehall-admin.production.alphagov.co.uk/government/uploads/system/uploads/attachment_data/file/68947/supplementary.docx. Accessed 8 Mar 2013
Hockley N, Edwards-Jones G (2009) Growing food and fibre in a constrained world. In: Hemery G (ed). Timber, mutton or fuel? Debating the economics of land use and forestry. Proceedings of the ICF National Conference 2009. Cardiff
Hoen HF, Solberg B (1994) Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. For Sci 40:429–451
Höhne N, Kejun J, Rogelj J, Segafredo L, Seroa da Motta R, Shukla PR, Angelsen A, Blok K, Chen C, Cruz R, Dalkmann H, Dellink R, den Elzen M, Egan C, Façanha C, Gesteira C, Graham P, Hargrave J, Hanaoka T, Karpay D, Levin K, Lowe J, Luderer G, Montzka S, Olivier J, Pestiaux J, Sawin E, Schaeffer M, Schaeffer R, Taylor C, Ton M, Ürge-Vorsatz D, van Vuuren D, Wagner F, Wunder S, and Xiusheng Z (2012) The emissions gap report 2012. UN Environmental Programme, Nairobi. http://www.unep.org/pdf/2012gapreport.pdf. Accessed 5 Mar 2013
IEA (2011) World Energy Outlook, press and media, quotes. International Energy Authority. http://www.iea.org/publications/worldenergyoutlook/pressmedia/quotes/5/. Accessed 13 Nov 2012

IPCC (2001) Climate Change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. In: Houghton J, Ding Y, Griggs D, Noguer M, van der Linden P, Dai X, Maskell K, Johnson C (eds) Cambridge University Press, Cambridge, UK, http://www.grida.no/publications/other/ipcc_tar/. Accessed 23 Jan.2013

IPCC (2005) Carbon dioxide capture and storage. Cambridge University Press, Cambridge, UK

IPCC (2007a) Climate change 2007: synthesis report. Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

IPCC (2007b) Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

IPCC (2012) Meeting report of the intergovernmental panel on climate change expert meeting on Geoengineering. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Field C, Barros V, Stocker TF, Dahe Q, Minx J, Mach K, Plattner G-K, Schlömer S, Hansen G, Mastrandrea M (eds) IPCC Working Group III technical support unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany. http://www.ipcc-wg3.de/meetings/expert-meetings-and-workshops/em-geoengineering. Accessed 7 Nov.2012

Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritze R, Hagedorn F, Johnson DW, Minkkinen K, Byrne KA (2007) How strongly can forest management influence soil carbon sequestration? Geoderma 137:253–268

Jarvis P, Clement R, Grace J, Smith K (2009) The role of forests in the capture and exchange of energy and greenhouse gases. Chapter 3. In: Read D, Freer-Smith P, Morrison J, Hanley N, West C, Snowdon P (eds) Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh, pp 21–49

Jorgensen DW, Wilcoxen PJ (1990) The cost of controlling US carbon dioxide emissions. Quoted in Cline (1992)

Keith DW, Parson E, Morgan MG (2010) Research on global sun block needed now. Nature 463:426–427

Kesicki F (2011) Marginal abatement cost curves for policy-making – expert-based vs model-derived curves. UCL Energy Institute, University College London. www.homepages.ucl.ac.uk/~ucft347/Kesicki_MACC.pdf. Accessed 5 Mar 2013

Latin H (2012) Climate change policy failures: why conventional mitigation approaches cannot succeed. World Scientific, London

Le Page M (2012) Global warming/global warning. New Sci 216(2891):34–39

Lenton T, Held H, Kreigler E, Hall J, Lucht W, Rahmstorf S, Schellnhuber H (2008) Tipping elements in the Earth's climate system. Natl Acad Sci USA 105(6):1786–1793

Lind RC (ed) (1982) Discounting for time and risk in energy policy. Johns Hopkins University Press, Baltimore

Lorenz K, Lal R (2010) Carbon sequestration in forest ecosystems. Springer, London

Lowe J (2008) Intergenerational wealth transfers and social discounting: supplementary Green Book guidance. HM Treasury, London, http://www.hm-treasury.gov.uk/d/4(5).pdf. Accessed 17 Jan 2013

Lüthi D, Le Floch M, Bereiter B, Blunier T, Barnola J-M, Siegenthaler U, Raynaud D, Jouzel J, Fischer H, Kawamura K, Stocker T (2008) High-resolution carbon dioxide concentration record 650,000-800,000 years before present. Nature 453:379–382, http://www.nature.com/nature/journal/v453/n7193/pdf/nature06949.pdf. Accessed 5 Mar 2013

Mahli Y, Meir P, Brown S (2002) Forests, carbon and global climate. Philo Trans R Soc Lond 360:1567–1591

Matthews RW, Broadmeadow MSJ (2009) The Potential of UK forestry to Contribute to Government's Emissions Reduction Commitments. In: Read DJ, Freer-Smith PH, Morison JIL, Hanley N, West CC, Snowdon P (eds) In Combating climate change – a role for UK forests – an assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh, pp 139–161

Moran D, Macleod M, Wall E, Eory V, Pajot G, Matthews R, Mcvittie A, Barnes A, Rees B, Moxey A, Williams A, Smith P (2008) UK marginal abatement cost curves for agriculture and land

use, land-use change and forestry sectors out to 2022, with qualitative analysis of options to 2050. Final Report to the Committee on Climate Change, London

Morison JIL, Matthews R, Miller G, Perks M, Randle T, Vanguelova E, White M, Yamulki S (2012) Understanding the carbon and greenhouse gas balance of UK forests. Report for Forestry Commission, Forest Research

Moxey A (2011) Illustrative economics of peatland restoration. Report to IUCN UK Peatland Programme. www.iucn-uk-peatlandprogramme.org/scientificreviews. Accessed 5 Mar 2013

Murray B, McCarl B, Lee H-C (2004) Estimating leakage from forest carbon sequestration programs. Land Econ 80(1):109–124

Murray B, Lubowski R, Sohngen B (2009) Including international forest carbon incentives in climate policy: understanding the economics. Nicholas Institute, Duke University, USA, www.nicholas.duke.edu/institute/carbon.economy.06.09.pdf. Accessed 5 Mar 2013

Nabuurs G, Masera O, Andrasko K, Beneez-Ponce P, Boer R, Dutschke M, Elsiddig E, Ford-Robertson J, Frumhoff P, Karjalainen T, Krankina O, Kurz W, Matsumoto M, Oyhantcabal W, Ravindranath N, Sanz Sanchez M, Zhang X (2007) Forestry. In climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press

National Academy of Sciences (1991) Policy implications of greenhouse warming. National Academy Press, Washington, DC

Nijnik M, Pajot G, Moffat A, Slee B (2013) An economic analysis of the establishment of forest plantations in the United Kingdom to mitigate climate change. For Policy Econ 26:34–42

Nisbet T (2005) Water use by trees. Information Note, Forestry Commission, Edinburgh, http://www.forestry.gov.uk/forestry/infd-8bvgx9

Nisbet T, Marrington S, Thomas H, Broadmeadow S, Valatin G (2011) Slowing the flow at pickering, final report to Defra of FCERM multi-objective flood management demonstration project RMP5455. Forest Research, Farnham, http://www.forestry.gov.uk/fr/INFD-7ZUCQY#final1. Accessed 5 Mar 2013

Nordhaus W (1991) To slow or not to slow: the economics of the greenhouse effect. Econ J 101:920–937

Nordhaus WD (1993) Rolling the 'DICE': an optimal transition path for controlling greenhouse gases. Resour Energy Econ 15:27–50

Nordhaus WD (2007) A review of the Stern review on the economics of climate change. J Econ Lit 45:686–702

OECD (2009) The economics of climate change mitigation: policies and options for Global action beyond 2012. OECD, Paris, http://www.oecd.org/document/32/0,3746,en_2649_34361_41951200_1_1_1_1,00.html

Office of Management and Budget (various years) Budget of the United States Government. Office of Management and Budget, Washington, DC

OFGEM (2012) Feed-in Tariff Payment Rate Table for Photovoltaic Eligible Installations for FIT Year 3 (2012/13). Gas and Electricity Markets Authority (OFGEM), London. http://www.ofgem.gov.uk/Sustainability/Environment/fits/tariff-tables/Pages/index.aspx. Accessed 10 Jan 2013

Olschewski R, Benitez PC (2010) Optimizing joint production of timber and carbon sequestration of afforestation projects. J For Econ 16:1–10

OXERA (2002) A social time preference rate for use in long-term discounting. OXERA Consulting/Office of the Deputy Prime Minister, Department for Transport, Department for the Environment and Rural Affairs, London

Pearson P, Palmer M (2000) Atmospheric carbon dioxide concentrations over the past 60 million years. Nature 406:695–699

Peters G, Andrew R, Boden T, Canadell J, Ciais P, Le Quéré C, Marland G, Raupach M, Wilson C (2013) The challenge to keep global warming below 2°C. Nat Clim Chang 3:4–7

Peters-Stanley M, Hamilton K (2012) Developing dimension: state of the voluntary carbon markets 2012. Forest Trends, Washington, DC, http://www.forest-trends.org/publication_details.php?publicationID=3164, Accessed 5 Mar 2013

Portney PR, Weyant JP (eds) (1999) Discounting and intergenerational equity. Resources for the Future, Washington, DC

Pöyry Energy Consulting (2007) Analysis of carbon capture and storage cost–supply curves for the UK. Pöyry Energy, Oxford

Price C (1973) To the future: with indifference or concern? The social discount rate and its implications in land use. J Agric Econ 24:393–398

Price C (1984) Project appraisal and planning for over-developed countries. Environ Manage 8:221–242

Price C (1988) Does social cost-benefit analysis measure overall utility change? Econ Lett 26:357–361

Price C (1990) The allowable burn effect: a new escape from the bogey of compound interest. For Chron 66:572–578

Price C (1993) Time, discounting and value. Blackwell, Oxford, Also freely available in electronic format from c.price@bangor.ac.uk

Price C (1997) Analysis of time profiles of climate change. In: Adger WN, Pettenella D, Whitby M (eds) Climate change mitigation and European land use policies. CAB International, Wallingford, pp 71–87

Price C (2003) Diminishing marginal utility: the respectable case for discounting? Int J Sustain Dev 6:117–132

Price C (2005) How sustainable is discounting? In: Kant S, Berry AL (eds) Sustainability, economics and natural resources: economics of sustainable forest management. Springer, Amsterdam, pp 106–135

Price C (2006) Economics of sustainable development: reconciling diverse intertemporal perspectives. In Encyclopaedia of Life Support Systems (electronic book, no page numbers). EoLSS Publishers, Ramsey

Price C (2007) Sustainable forest management, pecuniary externalities and invisible stakeholders. For Policy Econ 9:751–762

Price C (2010) Low discount rates and insignificant environmental values. Ecol Econ 69:1895–1903

Price C (2011) Optimal rotation with declining discount rate. J For Econ 17:307–318

Price C (2012) Rising carbon flux price and the paradoxes of forest-based reduction of atmospheric carbon stock: an extended summary. Scand For Econ 44:240. Full manuscript available from the author

Price C (in review) A nightmare waiting in the wings: the social cost of carbon, forest economics and declining discount rates. Manuscript submitted to Journal of Forest Economics. Available from the author

Price Waterhouse Cooper (2012) Too late for two degrees? Low carbon economy index 2012. http://www.pwc.com/en_GX/gx/low-carbon-economy-index/assets/pwc-low-carbon-economy-index-2012.pdf. Accessed 26 Nov 2012

Price C, Willis R (1993) Time, discounting and the valuation of forestry's carbon fluxes. Commonw For Rev 72:265–271

Price C, Willis R (2011) The multiple effects of carbon values on optimal rotation. J For Econ 17:298–306

Radov D, Klevnas P, Skurray J, Harris D, Chambers B, Chadwick D, Dyer R, Nagler D (2007) Market mechanisms for reducing GHG emissions from agriculture, forestry and land management. NERA Economic Consulting, Defra, London

Ramanathan V, Feng Y (2008) On avoiding dangerous anthropogenic interference with the climate system: formidable challenges ahead. Natl Acad Sci USA 105(38):14245–14250

Ramsey FP (1928) A mathematical theory of saving. Econ J 38:543–559

Read DJ, Freer-Smith PH, Morrison JIL, Hanley N, West CC, Snowdon P (eds) (2009) Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh, http://www.tsoshop.co.uk/gempdf/Climate_Change_Main_Report.pdf. Accessed 24 Jan 2013

Richards K, Andersson A (2001) The leaky sink: persistent obstacles to a forest carbon sequestration program based upon individual projects. Clim Policy 1:41–54

Richards KR, Stokes C (2004) A review of forest carbon sequestration cost studies: a dozen years of research. Clim Change 63:1–48
Riebeek H (2011) The carbon cycle. Earth Observatory, NASA. http://earthobservatory.nasa.gov/Features/CarbonCycle/. Accessed 7 Nov 2012
Robock A, Marquardt A, Kravitz B, Stenchikov G (2009) Benefits, risks, and costs of stratospheric geoengineering. Geophys Res Lett 36, L19703
Royal Society (2009) Geoengineering the climate: science, governance and uncertainty. Royal Society, London, http://royalsociety.org/policy/publications/2009/geoengineering-climate/. Accessed 5 Mar 2013
Sedjo RA, Ley E (1997) The potential role of large-scale forestry in Argentina. In: Adger WN, Pettenella D, Whitby M (eds) Climate change mitigation and European land use policies. CAB International, Wallingford, pp 255–268
Sedjo RA, Solomon AM (1989) Climate and forests. In: Rosenberg NJ et al (eds) Greenhouse warming: abatement and adaptation. Resources for the Future, Washington, DC, pp 105–119
Schellnhuber H (2008) Global warming: stop worrying, start panicking? Natl Acad Sci USA 105(38):14239–14240
Schellnhuber H (2011) Geoengineering: the good, the MAD, and the sensible. Natl Acad Sci USA 108(51):20277–20278
Schellnhuber HJ (2012) Reply to Schuiling: last things last. Natl Acad Sci USA 109(20):E1211. http://www.pnas.org/content/109/20/E1211.full.pdf+html. Accessed 7 Nov 2013
Schuiling R (2012) Capturing $CO_2$ from the air. Natl Acad Sci USA 109(20):14239–14240
Schuur E, Abbott B (2011) High risk of permafrost thaw. Nature 480:32–33
Sohngen B (2009) An analysis of forestry carbon sequestration as a response to climate change. Copenhagen Consensus Center, Copenhagen, http://fixtheclimate.com/component-1/the-solutions-new-research/forestry
Sohngen B, Sedjo R (2006) Carbon sequestration costs in global forests. Energy J, Special Issue 27:109–126
Spash C (1994) Double $CO_2$ and beyond: benefits, costs and compensation. Ecol Econ 10:27–36
Spash C (2002) Greenhouse economics: value and ethics. Routledge, London
Spencer I, Bann C, Moran D, Mcvittie A, Lawrence K, Caldwell V (2008) A framework for environmental accounts for agriculture. Report SFS0601 by Jacobs with Scottish Agricultural College and Cranfield University to DEFRA Welsh Assemby Government, Scottish Government, and DARD (N Ireland), London
Stern N (2006) The economics of climate change, HM Treasury/Cambridge University Press. http://www.hm-treasury.gov.uk/stern_review_report.htm. Accessed 5 Mar 2013
Thompson D, Matthews R (1989) $CO_2$ in trees and timber lowers greenhouse effect. Forestry and British Timber October:19–24
Treasury HM (2003) The green book: appraisal and evaluation in central government. The Stationery Office, London
Trumper K, Bertzky M, Dickson B, van der Heijden G, Jenkins M, Manning P (June 2009) The natural fix? The role of ecosystems in climate mitigation. A UNEP rapid response assessment. United Nations Environment Programme, UNEPWCMC, Cambridge. http://www.grida.no/publications/rr/natural-fix/. Accessed 5 Mar 2013
UNFCCC (2008) Report of the conference of the parties on its thirteenth session, held in Bali from 3 to 15 December 2007. Part two: action taken by the Conference of the Parties at its thirteenth session. United Nations Convention on Climate Change, Decision 2/CP.13, FCCC/CP/2007/6/Add.1. http://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf. Accessed 5 Mar 2013
UNFCCC (2010) Report of the conference of the parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009. Part two: action taken by the conference of the parties at its fifteenth session. United Nations Convention on Climate Change, FCCC/CP/2009/11/Add.1 http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf. Accessed 5 Mar 2013
UNFCCC (2011) Report of the conference of the parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. Part two: action taken by the conference of the parties

at its sixteenth session. United Nations Convention on Climate Change, FCCC/CP/2010/7/Add.1. http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf. Accessed 5 Mar 2013

Valatin G (2005) Justice, human security and the environment, PhD Dissertation, Economics Department, University of Siena

Valatin G (2011a) Forests and carbon: a review of additionality. Research Report. Forestry Commission, Edinburgh, http://www.forestry.gov.uk/fr/INFD-7WUEAN. Accessed 5 Mar 2013

Valatin G (2011b) Forests and carbon: valuation, discounting and risk management. Research Report, Forestry Commission, Edinburgh, http://www.forestry.gov.uk/fr/INFD-7WUEAN. Accessed 5 Mar 2013

Valatin G (2012) Marginal abatement cost curves for UK forestry. Research Report 19, Forestry Commission, Edinburgh, http://www.forestry.gov.uk/PDF/FCRP019.pdf/$FILE/FCRP019.pdf. Accessed 5 Mar 2013

Valatin G, Saraev V ((2012) Natural environment framework: woodland creation case study. Report to Forestry Commission Wales, Forest Research, Edinburgh, http://www.forestry.gov.uk/fr/INFD-8YAECD. Accessed 5 Mar 2013

Valatin G, Starling J (2011) Valuation of ecosystem services provided by UK woodlands, appendix to chapter 22 of UK National Ecosystem Assessment. UNEP-WCMC/Defra, London

van Kooten GC, Sohngen B (2007) Economics of forest ecosystem carbon sinks: a review. Int Rev Environ Resour Econ 1:237–269

van Kooten GC, Johnston C, Xu Z (2012) Economics of forest carbon sequestration. Working paper 2-12-4, Resource Economics and Policy Analysis Research Group. University of Victoria, Canada

Weikard H-P, Wangler L, Freytag A. (2009). Minimum participation rules with heterogeneous countries. Jena Economic Research Papers, zs.thulb.uni-jena.de/receive/jportal_jparticle_00156984

Worrall F, Chapman P, Holden J, Evans C, Artz R, Smith P, Grayson R (2011) A review of current evidence on carbon fluxes and greenhouse gas emissions from UK peatlands. Joint Nature Conservation Committee, Peterborough, www.jncc.defra.gov.uk/pdf/jncc442_webFinal.pdf. Accessed 5 Mar 2013